DESIGN STUDY OF A STRAIN GAUGE WIND TUNNEL BALANCE

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THESIS

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STRAIN GAUGE WIND TUNNEL BALANCE

by

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March 1974

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by

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ABSTRACT

A three-component balance system for use in measuring drag and lift forces as well as pitching moments acting on a wind tunnel model is presently available in the Department of Aeronautics. The original manual counterweight readout procedure was considered obsolete from the standpoint of data acquisition; therefore, a revision was incorporated using strain gauge load cells. The design and installation of the electrical readout system was accomplished. Calibration procedures were devised and performed in order to develop a loading output matrix for use with a rapid data acquisition system and compatibility with an analog-digital computer program.

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Latin Symbols

C_D	Drag coefficient, dimensionless
C_L	Lift coefficient, dimensionless
C_M	Pitching moment coefficient, dimensionless
D	Drag force, lbs
E	Modulus of elasticity, lbs/in^2
F_x	Restraint force in flexure x, lbs
I_x	Moment of inertia of element x, in^4
Δk_p	Deflection at point of load application, in
L	Lift force, lbs
M	Pitching moment/bending moment, in-lbs
P	Applied load, lbs
P_x	Loading in force flexure x, lbs
U	Elastic strain energy, in-lbs

Greek Symbols

α	Angle of attack, radians
Δ	Difference or change in quantity
ϵ	Strain, in/in
θ	Deflection angle, radians
σ	Normal stress, lb/in^2
σ_x	Standard deviation of quantity x

I. INTRODUCTION

The Aeronautical Engineering Department of the Naval Postgraduate School possesses two subsonic wind tunnels for use in the Department curricula and for student research. The two-stage drive tunnel has a maximum velocity of two hundred miles per hour and a test section that measures three and one-half by five feet. The single-stage drive tunnel also has a maximum velocity of two hundred miles per hour and has a test section size of thirty-two by forty-five inches.

Any requirements for force measurement in wind tunnels must be met through the use of one AEROLAB 543 wind tunnel balance. Although this balance is capable of measuring both longitudinal and lateral forces with a high degree of accuracy, it is a beam type balance that requires mechanical manipulation in order to read the loads on the model. Aerodynamic coefficients must be calculated by using additional information acquired from other sources. For these reasons, final results are not readily available for use in data interpretation during the course of the experiment.

It would be highly beneficial to any person conducting a wind tunnel test to have at his disposal immediate experimental results. This could be realized through the use of a rapid data acquisition system which would analyze balance loading, tunnel dynamic pressure and model size parameters. The use of a digital computer program which would require

reading-in of the above variables would be the primary method for rapid calculation of test results. Access to the program through the use of a terminal at the testing station would offer great flexibility. Many of the components for this type of operation are available in the Department of Aeronautics, such as those provided by Collier (Ref. 1) and Weinzapfel (Ref. 5). The integration of the complete data system would result in a routine production procedure.

The Aeronautical Engineering Department acquired a TASK MK I three component beam balance in October, 1958; the balance, for various reasons, has not been used for its intended purpose for a considerable length of time. This thesis serves primarily as a report on a design modification and testing of this balance as a proposed component of a data acquisition system such as described above. A second purpose of the thesis is to serve as an operational manual on the modified balance for future reference.

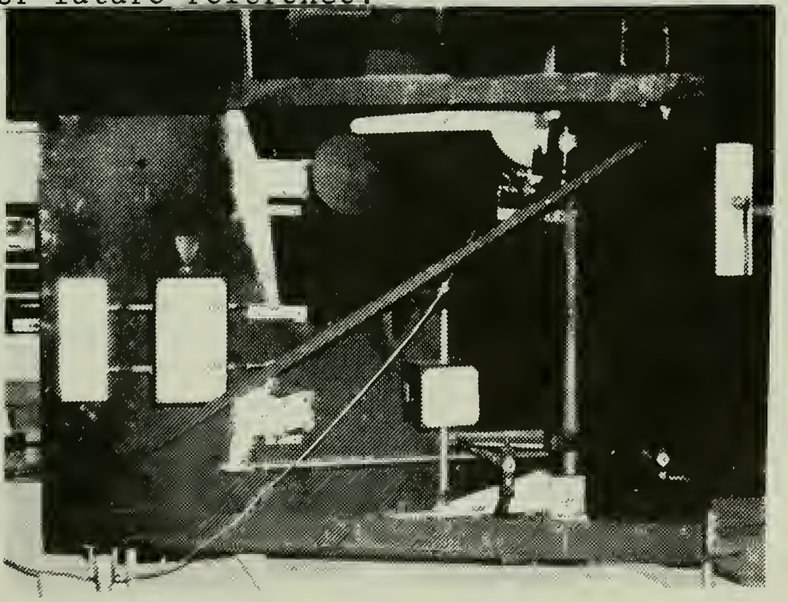


FIGURE 1
Task MK I Modified Balance

II. SYSTEM DESIGN

A. FUNDAMENTAL OBJECTIVES

The main objective of the project was the adaptation of the Task Corporation MK I three component beam balance so that it would provide consistent electrical output signals in order to form the principal element of a rapid data acquisition system for use in wind tunnel testing. The output was to be linear over the desired load ranges of the balance. These load ranges were chosen as five hundred pounds in lift, seventy-five pounds of drag and seventy-five foot pounds of moment; the desired ranges included both positive and negative values and were derived by considering a dynamic pressure of sixty pounds per square foot and a model wing area of three square feet in conjunction with a maximum lift coefficient of three, a maximum drag coefficient of four-tenths and a maximum pitching moment coefficient of five-tenths.

The electrical adaptation was required to have the capability to provide zero references for the longitudinal forces and angle of attack with a model in place on the balance. Provisions had to be made to ensure consistent output values under possible variances of power supply and other random disturbances.

B. AN INTERIM PROPOSAL

A proposal that was believed to meet the above stated

objectives was formulated previously. The design utilized reluctance gauge load cells to measure the forces in the internal mechanism of the balance. The deflections of the load cell rings were sensed by the reluctance gauges, which in turn transmitted electrical signals whose strength was proportional to the forces applied to the load cells.

The design eliminated the counterweight force measurement system of the original balance and appeared to be a reasonable solution. Once the design was fabricated, however, it was determined that the reluctance gauges were too sensitive to random disturbances and under applied loads produced unacceptable nonlinearities in their output signals. After a length of time spent in investigating these problems, the proposal was determined to be impractical. However, the reluctance gauge load cell design did verify that the use of electrical damping in a voltage signal that oscillated about an average value was feasible. In a mechanical balance as an analogy, viscous damping is provided through the use of adjustable dashpots in order to remove random load disturbances.

C. A FINAL PROPOSAL

Although the interim proposal was unusable because of the problems associated with the reluctance gauges, the concept of measuring forces applied to the balance through the use of load cells attached to its internal mechanism offered a prospective solution. The load cells were therefore

redesigned to use electrical strain gauges to measure load cell deflections. The new load cells were then fabricated and installed so as to replace the reluctance gauge load cells.

The resistance elements of the load cells formed a portion of a Wheatstone bridge circuit with the differential voltage output being handled by contemporary operational amplifier circuitry. Each bridge was designed to be powered by a five volt direct current supply, which was closely controlled by solid state regulators. The accuracy of these voltage regulators eliminated the need for separate adjustable power supplies for each bridge circuit.

A control box (figure 3) was fabricated which enclosed the power and signal conditioning circuits for the load cells. The face of the box contained four bridge balancing potentiometers for the three load cells and the angle of attack transducer attached to the angle of attack drive motor. The control box was powered by 110 VAC and has power/signal cables with quick disconnect fittings for attachment to the three load cell bridges and the angle of attack transducer.

The control box serves as a distribution point so as to route the output signals of the four bridge circuits to the multiplexing unit of a Digitec data acquisition and recording system (See figure 21). This arrangement allows rapid recording of four channels of output information

whose values are a measure of lift, drag and moment loads applied to the balance as well as of the angle of attack of a model.

In the final application, an additional signal processing unit would be employed which includes provision for electrical damping, scale adjust and signal monitoring. This unit was originally designed for use with the reluctance gauge load cell system and is intended as an interface between the load cell signal conditioning amplifiers and the output paper tape punch device that is a selectable mode of the Digitec console.

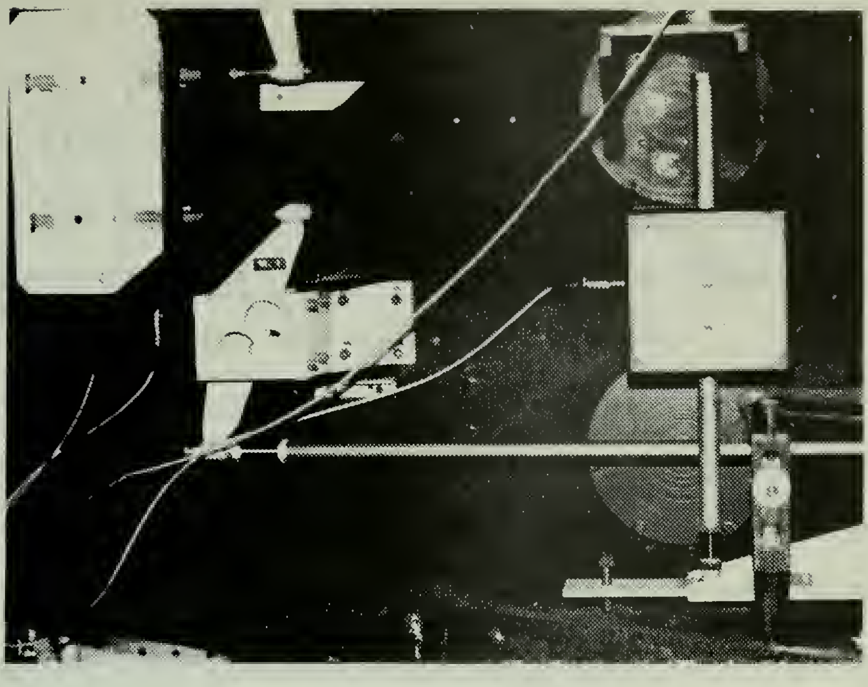


FIGURE 2

Load Cells and Connections

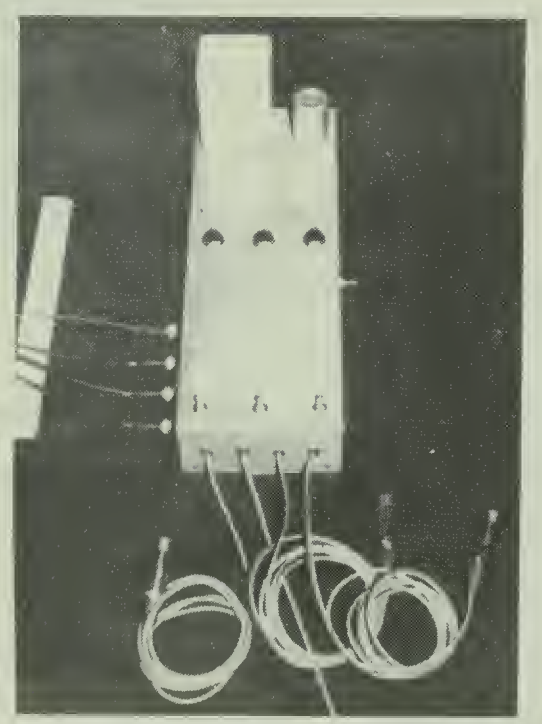


FIGURE 3

Balance Control Box

III. SYSTEM KINEMATICS

A. BASIC BALANCE STRUCTURE

The basic balance structure consists of a frame that encloses the balance mechanism and the primary support structure upon which the model is mounted.

The balance frame is a triangular base and two walled sides to which the internal balance mechanism is mounted. The base has castering wheels at each corner in order to provide a method of levelling the base of the balance. The top of the base serves as the floor of the balance. Two levels are attached to the floor and oriented at right angles to each other; the levels are used in conjunction with the levelling lugs in order to provide a horizontal reference platform. The walls of the balance frame are inelastic under the maximum loads specified for the balance. The outside of the back wall serves as a mounting point for an electrical multiple outlet and a vibrator motor. The inside of the back wall supports various lever axes and flexure rod anchor points.

The primary support member consists of a main column, a cross bar and model strut supports. The main column is a vertical hollow tube within which is mounted a vertical flexure for the transmission of lift forces. The main column serves as a method of transmitting model forces to the balance. It also serves as a foundation for a convenient model support system in the form of a cross bar to which the

span support struts are attached. A tail support arm is fastened to the upper area of the main column. This arm holds the tail support strut of the model, thus transmitting moment forces to the main column. An angle of attack motor can vary the position of the support arm so as to vary the angle of attack of the model. All support struts can be fastened to the cross bar and tail support arm so as to accommodate models of various proportions.

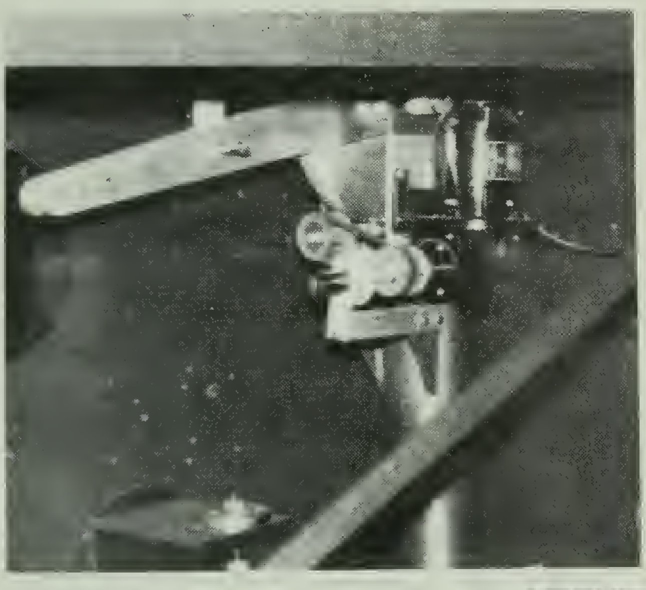


FIGURE 4

Tail Support Arm

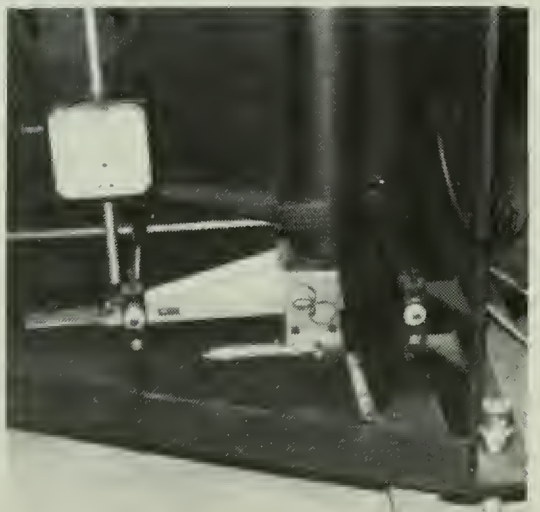


FIGURE 5

Balance Levels
and a Levelling Lug

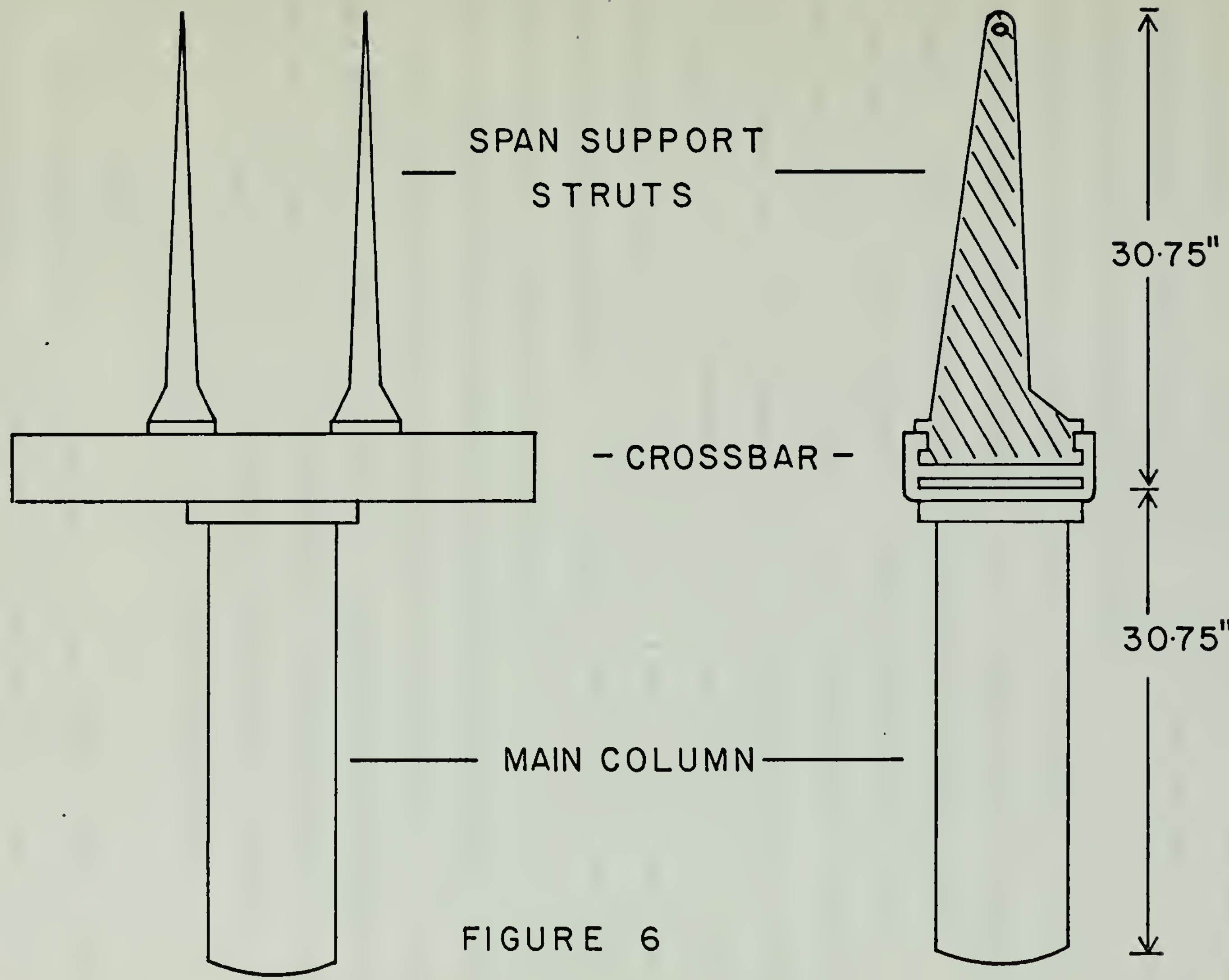


FIGURE 6

PRIMARY SUPPORT COLUMN

B. INTERNAL BALANCE MECHANISM

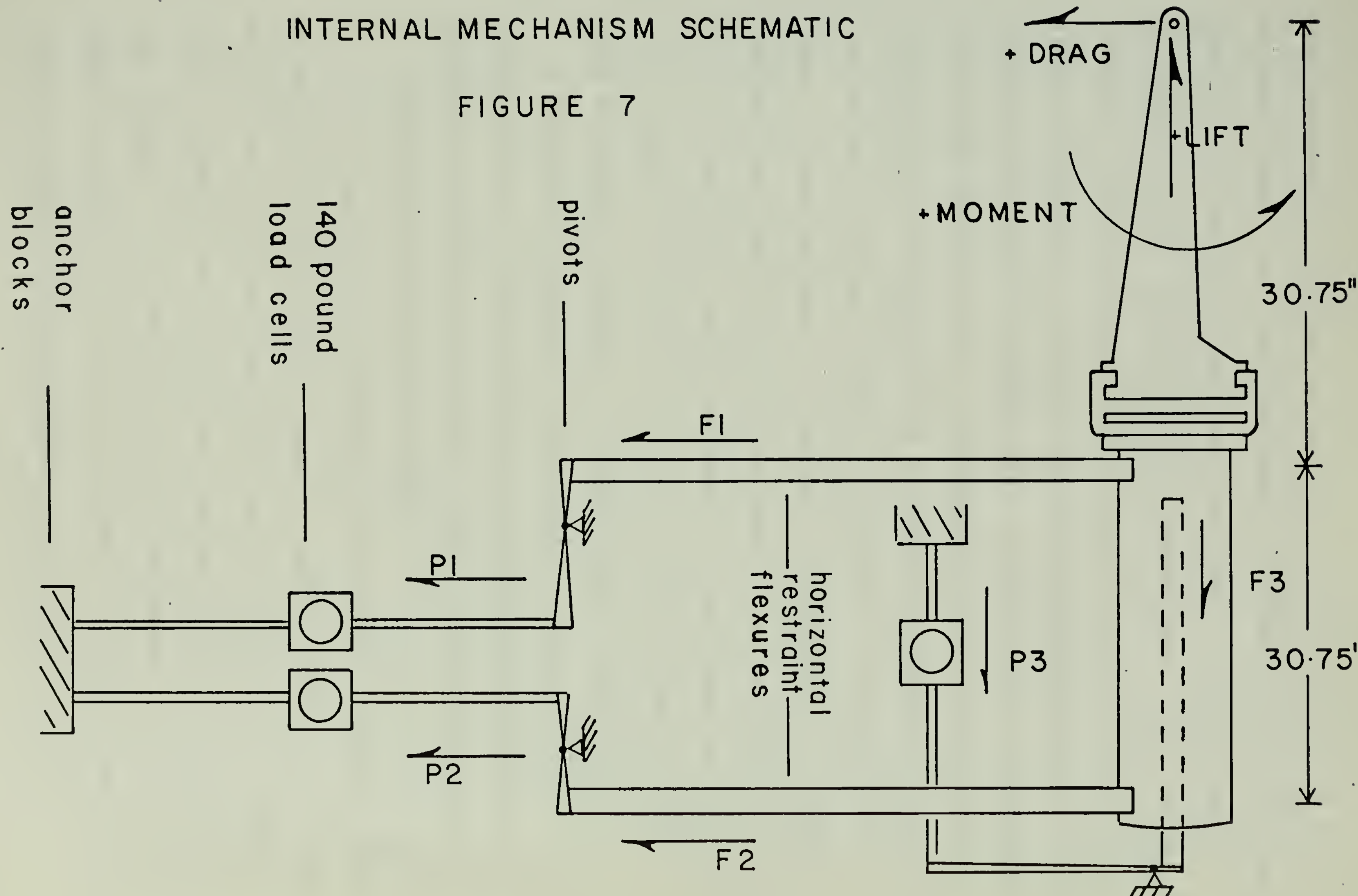
The general principle of the MK I balance is measurement of the longitudinal forces required to restrain the movement of the primary support member when it is subjected to a loading condition through its attachment to a test model. The internal balance mechanism serves to restrain the motion of the primary support member in the lateral and longitudinal planes. These restraints are provided by flexure rods attached to the main column is such a way as to fix its position relative to the frame. The longitudinal and vertical flexure rods transmit their restraining forces through linkages to force flexures that create deflections in the respective load cells. The lateral flexure rods have no transmission capability. The linkage and flexure arrangement serves to reduce the loads applied to the load cells and to confine the internal mechanism to reasonable dimensions.

The internal mechanism possesses a capability for some degree of adjustment in order to align the primary support member vertically. This adjustment is made possible by the use of threaded ends on both the flexure rods and force flexures. These adjustable ends provide variations in flexure length.

All flexures are constructed so that their ends consist of a web section that assures the forces are transmitted axially along the flexure. The webs are susceptible to damage from loads that have shear or torsional components. It is therefore very important that longitudinal flexures

INTERNAL MECHANISM SCHEMATIC

FIGURE 7



are oriented in a plane parallel to the back wall of the balance frame, and that the lateral flexures lie in a plane parallel to the front wall of the frame. All horizontal flexures must be parallel to the frame base. The anchor blocks to which one end of each force flexure is attached allow adjustment of the end in a plane perpendicular to the flexure axis such that the force flexures can be placed in the proper orientation. The remaining end of each force flexure and both ends of the restraint flexures are held in the proper position by their attachment to invariant fixtures. These degrees of freedom are necessary in order to provide the capability of disassembly and assembly of the balance as desired. When the above orientations are satisfied, all flexures are assured to carry their respective loads with no danger of damage to their fragile web ends.

A complete alignment of the balance consists of a horizontal base, a vertical primary support column and the flexure orientation discussed in the previous paragraph.

C. DERIVATION OF THE OUPUT MATRIX

By evaluating the condition of the static equilibrium as applied to the primary support member, the forces transmitted to the three load cells can be derived in a simple matrix format that yields the loading condition imposed on the balance. The addition of an independent equation with angle of attack as a variable produces a four element vector that describes the longitudinal state of the model.

Equating static forces:

$F_1 + F_2 + D = 0$

$F_3 + L = 0$

Moments about strut pinnacle:

$M - F_1 a - 2F_2 a = 0$

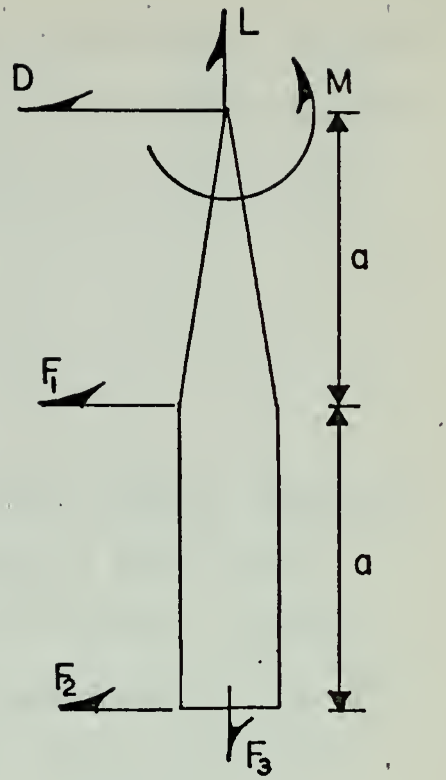
(a = 30.75 inches)

Solving for restraint forces:

$F_1 = -(M/a + 2D)$

$F_2 = (M/a + D)$

$F_3 = -(L)$



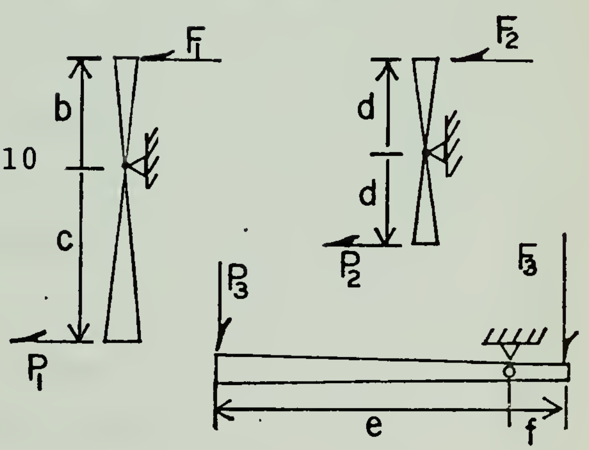
Applying leverage relations to restraint forces produces the forces measured by the load cells:

$b/c = 2/3 \quad d/d = 1 \quad f/e = 1/10$

$P_1 = -2/3F_1 = 2/3(M/a + 2D)$

$P_2 = -F_2 = -(M/a + D)$

$P_3 = -1/10F_3 = -1/10(L)$



Collecting the above expressions into a convenient matrix format:

$$\begin{Bmatrix} P_1 \\ P_2 \\ P_3 \end{Bmatrix} = \begin{bmatrix} 2/3 & 4/3 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & -1/10 \end{bmatrix} \begin{Bmatrix} M/a \\ D \\ L \end{Bmatrix} \qquad \begin{Bmatrix} M \\ D \\ L \end{Bmatrix} = \begin{bmatrix} -2a/3 & 4a/3 & 0 \\ 3/2 & 1 & 0 \\ 0 & 0 & -10 \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \end{Bmatrix}$$

Where $\{P\} = [C]\{F\}$ $\{F\} = [T]\{P\}$ $[T] = [C]^{-1}$

Since the state vector is in terms of the voltage outputs of the individual data channels, a conversion matrix must be formulated in order to produce an output vector in a more convenient format:

$$\{F\} = \begin{Bmatrix} M - (\text{in-lbs}) \\ D - (\text{lbs}) \\ L - (\text{lbs}) \end{Bmatrix}$$

by considering the slopes of the load cell outputs obtained from the calibration runs on the balance, a matrix was constructed that transformed load cell electrical signals into moment, drag and lift values in conventional units of measure. The method of obtaining the slopes of the calibration curves is explained in detail in Appendix B.

For the horizontal force flexures:

$$P_1 = (A_{11})\ M + (A_{12})\ D$$

$$P_2 = (A_{21})\ M + (A_{22})\ D$$

For the vertical force flexure:

$$P_3 = (A_{33})\ L$$

From the drag calibration curves:

$$P_1\ (\text{mv}) = +29.861\ (D\ \text{lbs})$$

$$P_2\ (\text{mv}) = -22.656\ (D\ \text{lbs})$$

From the moment calibration curves:

$$P_1\ (\text{mv}) = .491\ (M\ \text{in-lbs})$$

$$P_2\ (\text{mv}) = -.730\ (M\ \text{in-lbs})$$

From the lift calibration curves:

$$P_3 = 4.25\ (L\ \text{lbs})$$

Using this information, a coefficient matrix can be constructed:

$$\begin{Bmatrix} P_1 \text{ (mv)} \\ P_2 \text{ (mv)} \\ P_3 \text{ (mv)} \end{Bmatrix} = \begin{bmatrix} .491 & 29.861 & 0 \\ -.730 & -22.656 & 0 \\ 0 & 0 & 4.25 \end{bmatrix} \begin{Bmatrix} M \text{ (in-lbs)} \\ D \text{ (lbs)} \\ L \text{ (lbs)} \end{Bmatrix}$$

$\{P\} = [C]\{F\}$ $\{F\} = [C]^{-1}\{P\}$; $[C]$ is the coefficient matrix

$[C]^{-1} = [T]$ (The transformation or output matrix.)

In conclusion,

$$\begin{Bmatrix} M \text{ (in-lbs)} \\ D \text{ (lbs)} \\ L \text{ (lbs)} \end{Bmatrix} = \begin{bmatrix} -2.122 & -2.797 & 0 \\ .0684 & .046 & 0 \\ 0 & 0 & .235 \end{bmatrix} \begin{Bmatrix} P_1 \text{ (mv)} \\ P_2 \text{ (mv)} \\ P_3 \text{ (mv)} \end{Bmatrix}$$

IV. TESTING AND CALIBRATION PROCEDURE

A. ALIGNMENT OF INTERNAL MECHANISM

The alignment of all flexures is preferably carried out with the aid of a surveyor's transit and machinist's steel rule. The internal alignment should begin by blocking the wheels so that the balance will not accidentally roll, and then carefully levelling the base. The transit should first be placed so that the internal mechanism is viewed at approximately a right angle to the back wall of the frame. After levelling the transit, the lens can be swung in azimuth and elevation such that the horizontal grid of the transit passes through both webs of each horizontal force flexure. If this is not the case, then the flexure in question is not horizontal and the proper adjustment to the moveable end must be made. The vertical grid of the transit is used for alignment of the lift force flexure as explained in IV B.

The steel rule should be used to measure the distance of the web ends of the two drag force flexures from the back wall of the balance. If a force flexure is not parallel to the back wall, its orientation must be corrected by adjusting its moveable end. This method assures that the drag force flexures, horizontal restraint flexures, lift force flexure and lift restraint flexure all lie in the longitudinal plane of the balance.

With the transit in the same position relative to the

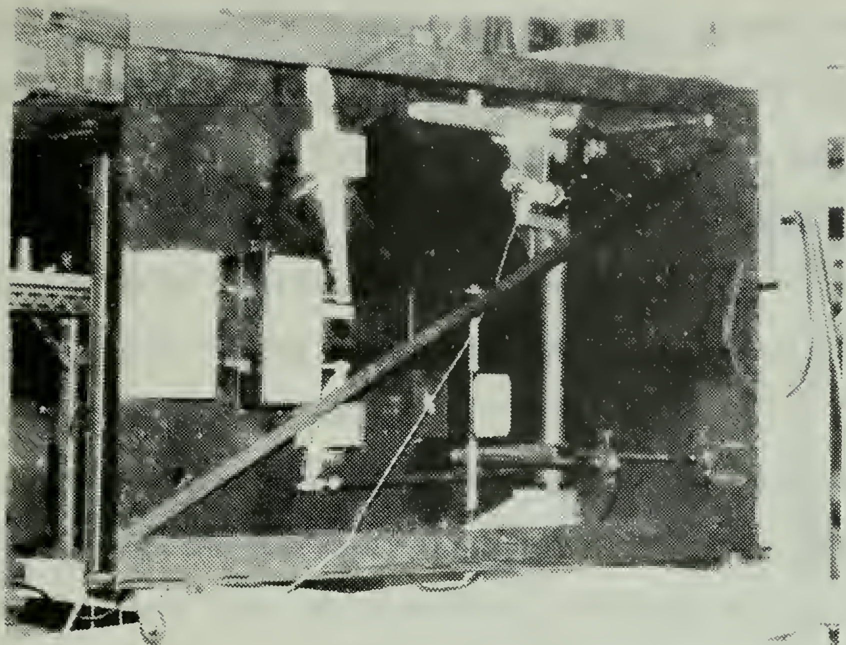
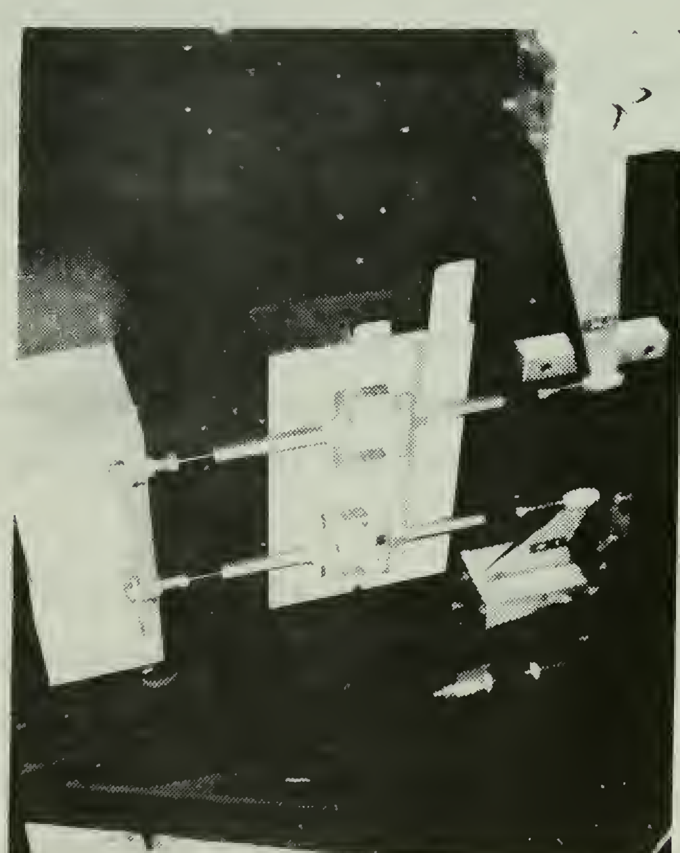


FIGURE 8

Lever arms and anchor blocks

FIGURE 9
Load cells and
Horizontal force
flexures



the main column. Adjustments to the primary support alignment are made by varying the length of the two pairs of horizontal restraint flexures attached to the main column. It is imperative that the primary support be examined from planes that contain the restraint flexures, so that any adjustment to the column in one plane does not move the column in the other.

When the above described alignment procedure has been completed, no further adjustment is necessary. As long as the balance base is levelled, the primary support member is vertical to the earth and therefore outputs will be accurate readings of the loads the balance is subjected to.

C. TESTING OF ELECTRICAL CIRCUITRY

All electrical apparatus for operation of the balance was connected to a common ground. The most readily available junction was the receptacle mounted to the balance back wall. The control box, vibrator, data acquisition system and angle of attack motor were joined to this receptacle. The receptacle in turn was connected to any available grounded electrical outlet. This method provided the desired common ground condition.

The power/signal cables from the control box were attached to the appropriate transducers by means of quick disconnect fittings. The multiplex cable was utilized between the control box and the data acquisition unit.

Proper voltage sensing was checked by means of hand

applied forces at the center of the crossbar. By pushing down on the crossbar, the lift load cell was to produce a negative voltage. When a basically horizontal force was applied toward the rear of the balance, approximately a positive drag force, the top drag load cell was to produce a positive voltage while the bottom cell produced a negative voltage. The angle of attack transducer was to produce an increasing positive voltage for an increasing model pitch angle. When any applied force was removed from the balance, the load cell readings returned to their original values. This insured that there was no electrical drift from the bridges' zero readings, which could be set by use of the potentiometers mounted on the face of the control box.

D. CALIBRATION OF THE BALANCE

1. General

The balance had to be calibrated for loading conditions of lift, drag, pitching moment and combinations of these three independent conditions. Calibration for angle of attack was also required. The various loadings required were achieved through the use of pan weights or hydraulically applied forces.

Loading the balance was accomplished through the use of a calibration bar designed for the purpose. The bar attached to the span support and tail struts much as a full model. The calibration bar had holes drilled into it such

that swage fittings could easily be attached to it. The swage fittings were mounted on steel cables that supported pan weights or hydraulic loads as appropriate. The cables were used because they were capable of being run over a pulley system in order to orient the applied loads horizontally or vertically as required.

For each type of applied load, the following initial procedures were completed prior to the calibration. First, the balance was secured such that it would not move as a load was applied to it, then the balance was carefully levelled. Once this was done, the installed calibration bar was levelled using the angle of attack motor. This was most easily accomplished with a precision level that rested on the calibration bar. The appropriate loading devices were next attached to the calibration bar, the vibrator motor turned on, and all four output channels were brought to zero voltage readings with their respective potentiometers.

The data for each calibration run were acquired in the following manner. First, a suitable incremental load was applied to the calibration bar. Ten-pound increments were used with pan weights and approximately fifty-pound increments when using the hydraulic method. If the load was by use of pan weights, the pan had to be steadied from its pendulum-like oscillations in order to obtain steady output readings. The Digitec multiplexing unit was then stepped through the three channels in order to read the digital voltmeter outputs and print out the values on the

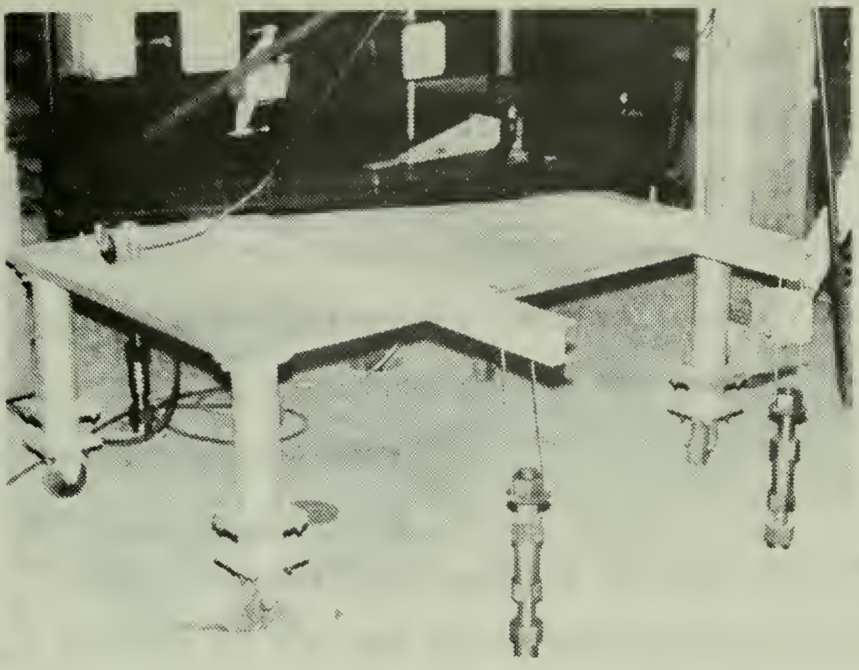
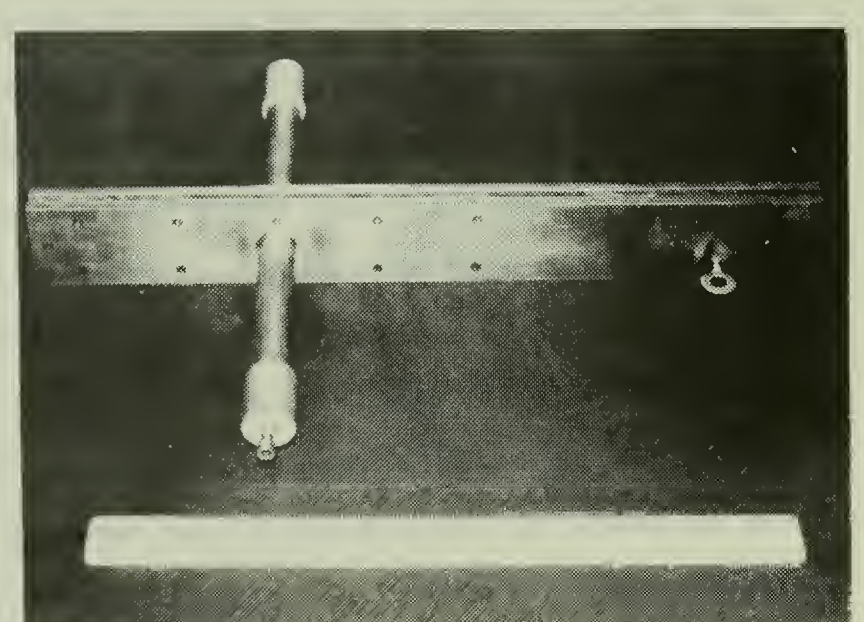


FIGURE 10

Balance Anchoring Procedure

FIGURE 11
Calibration bar



automatic recording device. Once the maximum desired load was reached, readings were also taken while reducing the load in increments in order to examine the data for evidence of hysteresis. The swage fittings were frequently checked for secure attachment to the calibration bar in order to prevent a serious accident due to the weights falling from their suspended position.

2. Lift Calibration

Negative lift was applied through pan weights; the swage fitting of the pan was suspended from the lower center hole of the calibration bar so that the center of gravity of the load was applied along the lift restraint flexure. One hundred fifty pounds was the maximum practical load that could be applied in negative lift due to balance size considerations.

Positive lift was applied hydraulically. The top center hole of the calibration bar was centered under the suspension point of the hydraulic piston used to create the loads. A plumb bob was required in order to assure exact alignment. A five hundred pound load cell was placed in the suspension system between the hydraulic piston and the calibration bar. The five hundred pound load cell was used to measure the load applied to the balance. Hydraulic pressure was supplied by a portable hand pump attached to the hydraulic piston. A small preload was first applied in order to bring the suspension system taut, then all balance output channels and the five hundred pound load cell bridge with its separate

DVM were zeroed before commencing the calibration. The maximum positive lift load applied was five hundred pounds, which transmitted the design maximum load of fifty pounds to the lift load cell.

3. Drag Calibration

Drag loading was accomplished using pan weights up to a total of seventy-five pounds. A frame structure and pulley assembly was used to orient a cable such that the pan weights would apply a horizontal load to the balance. The swage fitting on the cable was pinned to the endmost hole on the calibration bar. The balance was positioned such that when the cable was suspended over the pulley, it was colinear with the longitudinal axis of the calibration bar to which it was attached, and therefore the drag force was being applied along the longitudinal axis of the balance. The pulley was then adjusted in elevation such that the cable was horizontal. The surveyor's transit was used to make this adjustment.

4. Moment Calibration

The moment calibration procedure was carried out with the use of pan weights and hydraulic force. The balance was positioned such that either of the holes that defined the upper four inch moment arms of the calibration bar were directly beneath the suspension point of the hydraulic cylinder. The general procedure for creating and measuring the hydraulic force was the same as that used for lift calibration.

All moments up to four hundred inch pounds were applied by suspending pan weights from the appropriate moment arms of the calibration bar. Larger moments, up to the design maximum load of seventy-five foot pounds, had to be created hydraulically because suspending any more pan weights became physically impractical. Both the four inch and two inch moment arms were used to produce moment loadings when using suspended weights. This provided a cross check of balance alignment as discussed in Section VI.

5. <u>Angle of Attack Calibration</u>

Calibration of the angle of attack transducer did not require that the balance be positioned or levelled in any particular manner. The pitch drive system was positioned by means of its associated electrical controls attached to the forward wall of the balance. The controls encompassed start, stop, forward, reverse and speed functions. The geometric angle of the tail strut support arm was measured by a permanently installed rotary gauge on the back wall of the balance. Adjustable limit switches on this gauge serve to prevent damage to any particular model of exaggerated proportions due to contact with the balance as the model is rotated.

The pitch drive was first run to its full nose down attitude, of -36 degrees, and the transducer output voltage was set to a minimum output reference. The pitch mechanism was then rotated in successive nose up increments of five degrees and the output voltage recorded; this was

continued until the maximum positive pitch angle of +36 degrees was achieved.

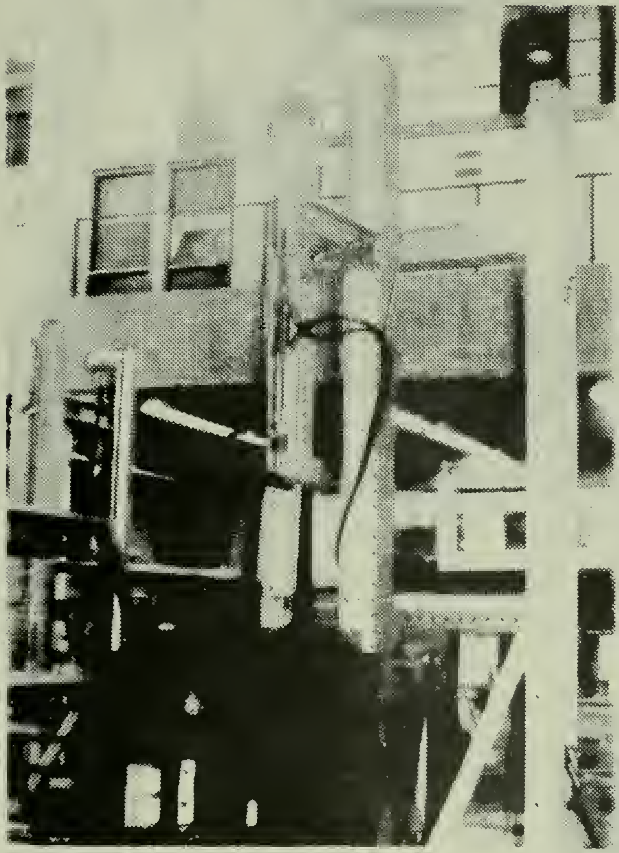


FIGURE 12

Hydraulic Load Assembly

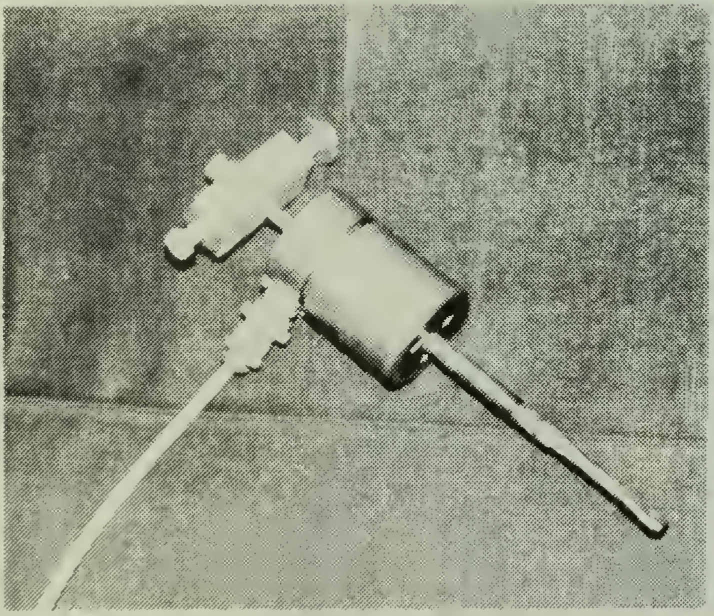


FIGURE 13

500 pound load cell

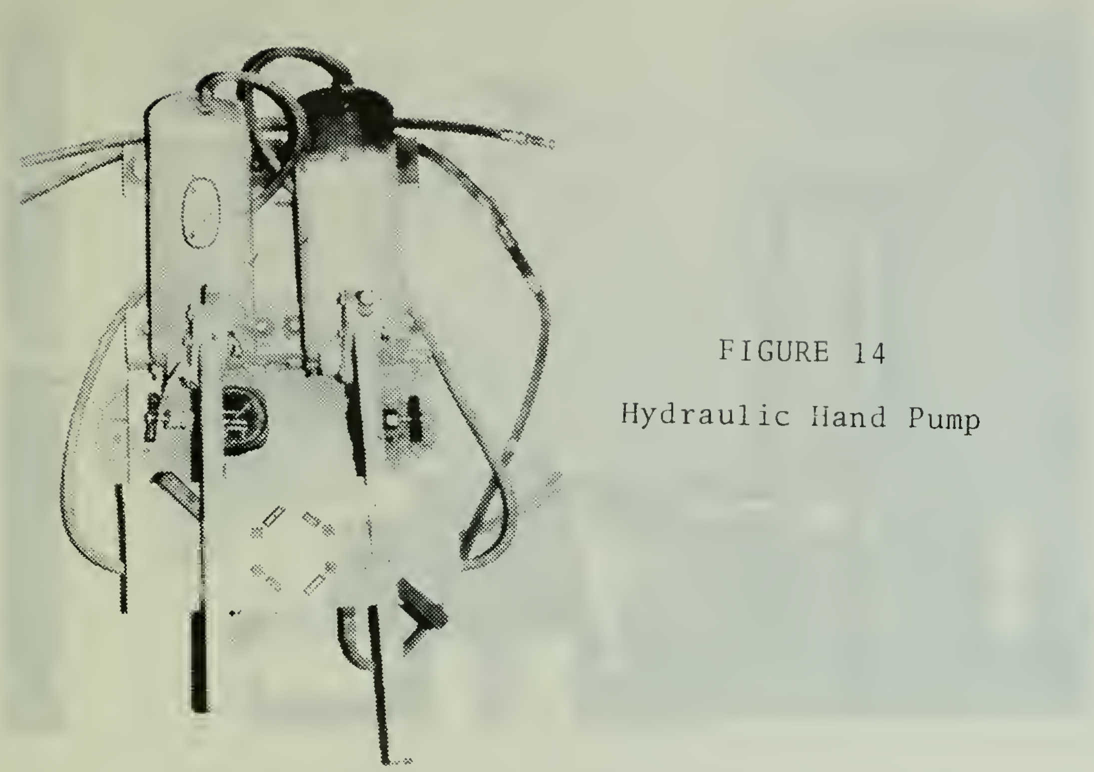


FIGURE 14

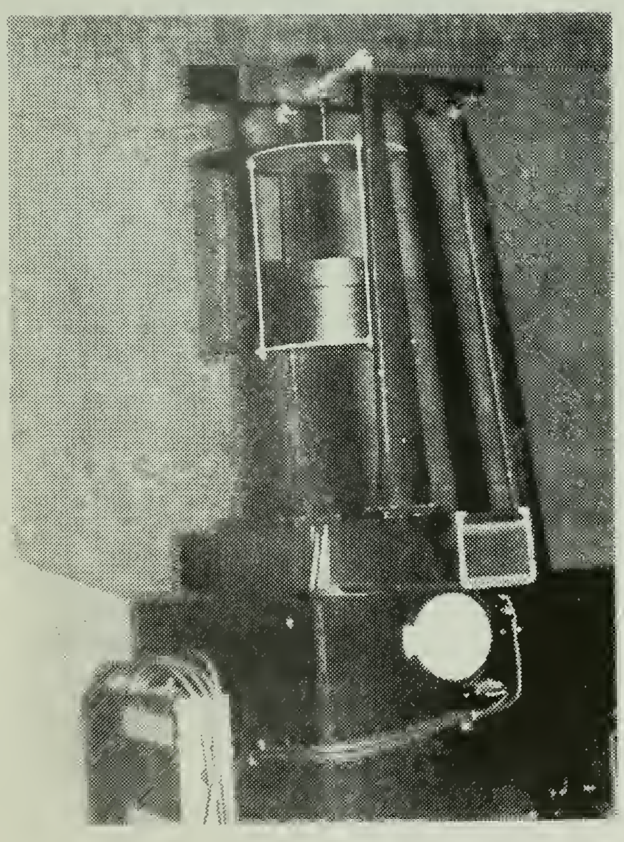
Hydraulic Hand Pump

FIGURE 15

Pan weights used to

apply negative lift

Calibration bar installed



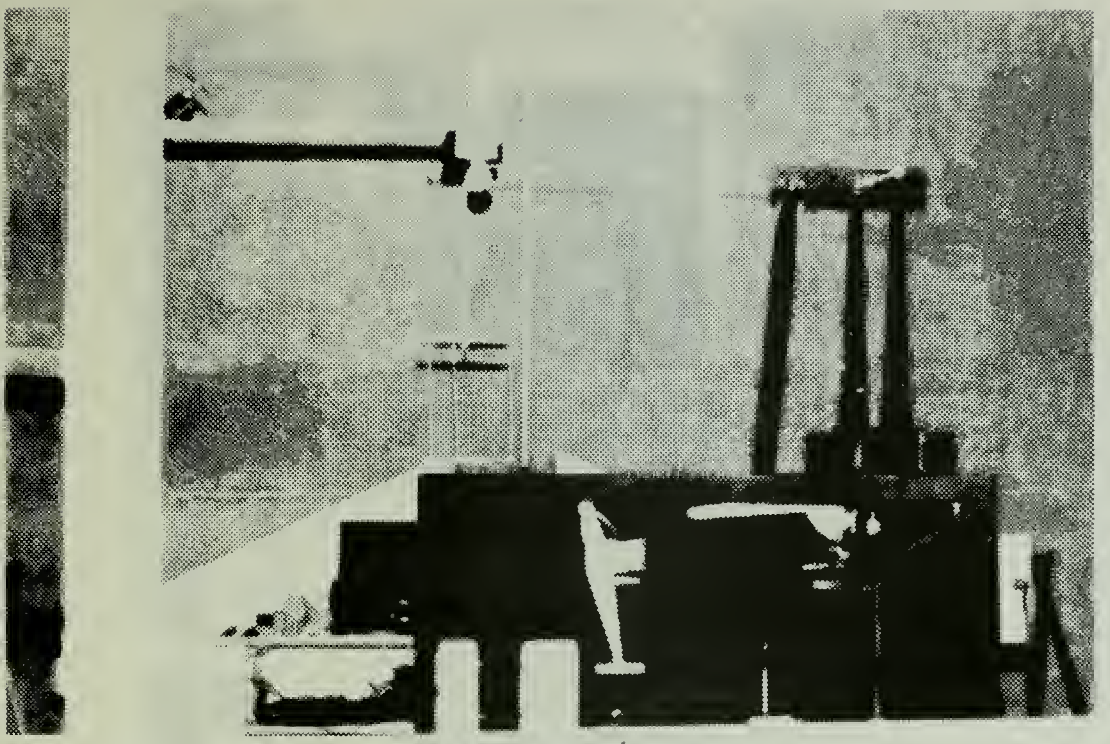


FIGURE 16

Drag Calibration Procedure

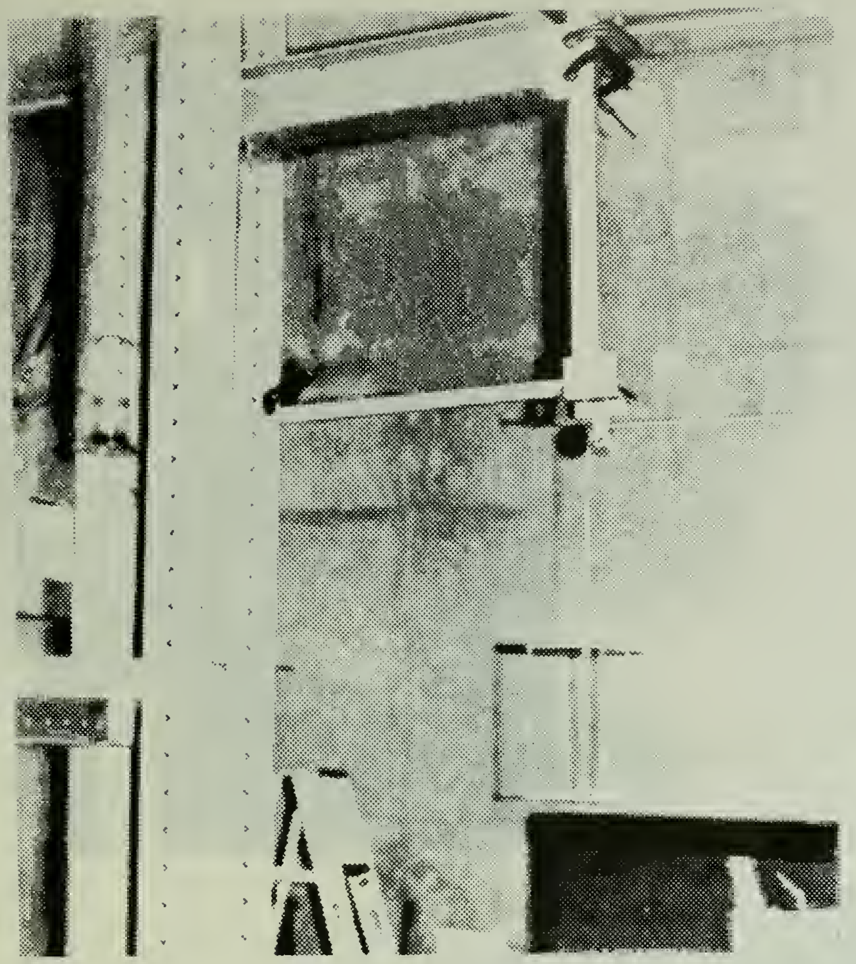


FIGURE 17

Drag Calibration Frame

Closeup

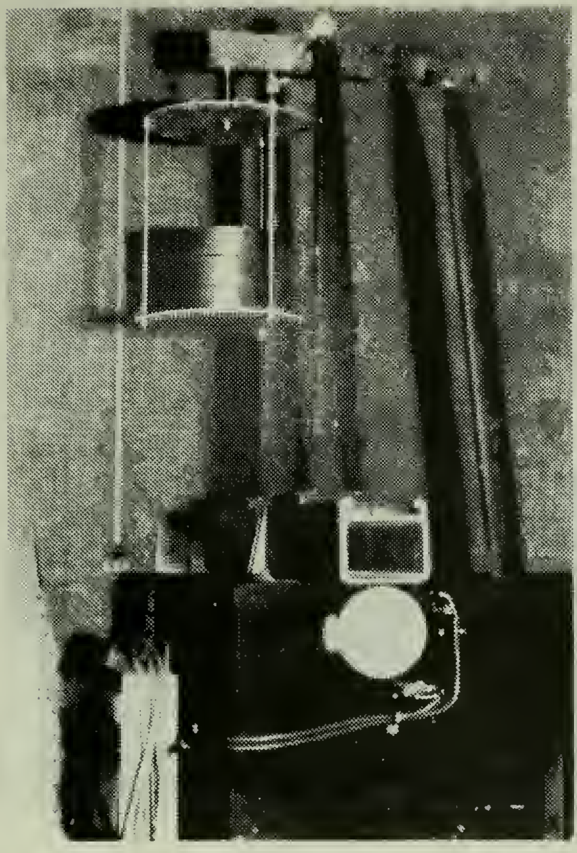


FIGURE 18

Negative moment
4 inch arm

Pan weight loading

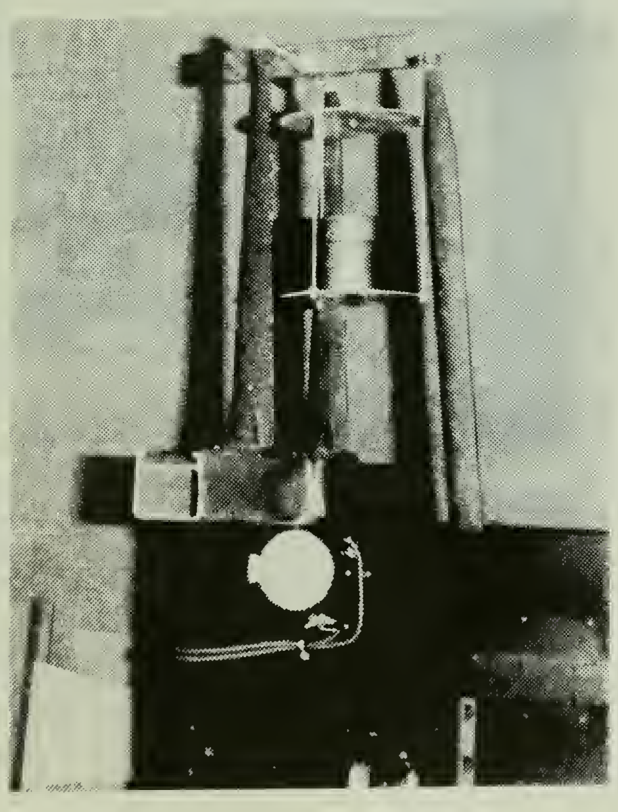


FIGURE 19

Positive moment

4 inch arm

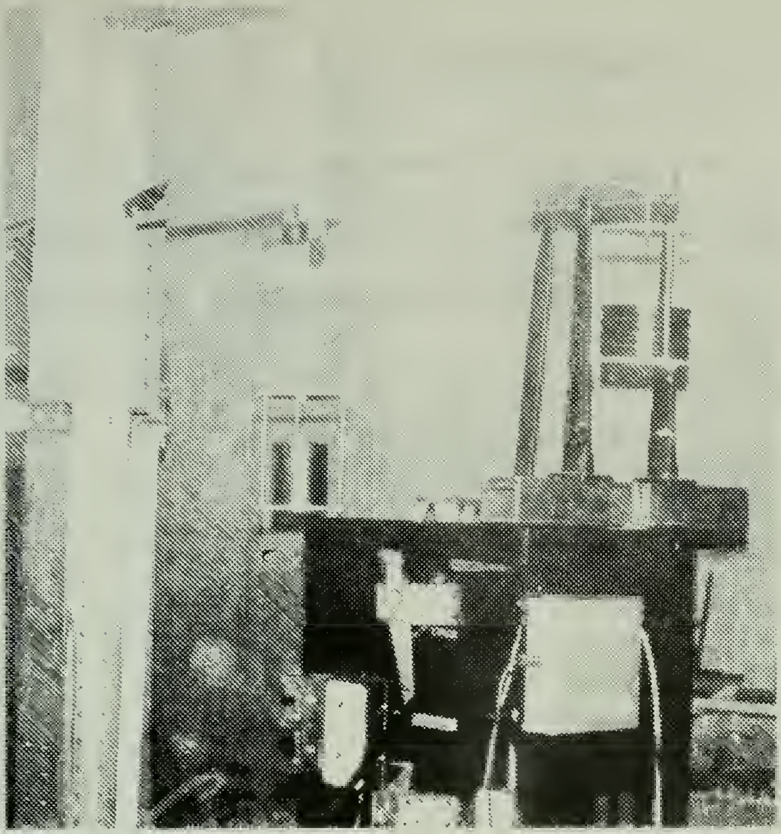


FIGURE 20

Combined loading procedure

FIGURE 21

Digitec data Acquisition console

V. PRESENTATION OF DATA

All calibration data are presented in tabular form. Each table of data is followed by a graphical plot except in the case of combined loadings.

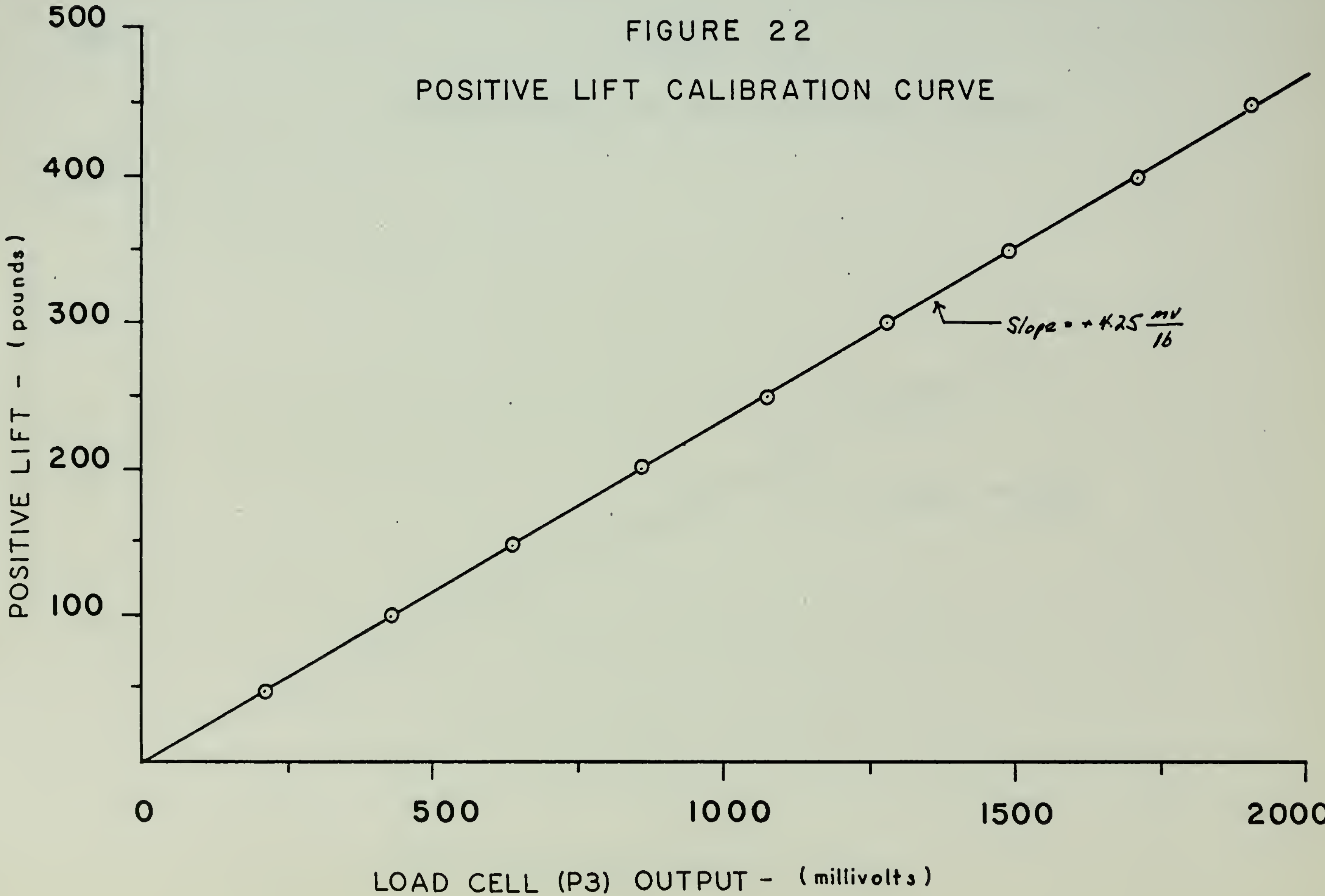
TABLE I

LIFT CALIBRATION DATA

LIFT LOAD pounds	LOAD CELL OUTPUT millivolts		
	P_1	P_2	P_3
0	0	0	0
50	0	0	212
100	0	0	423
150	0	0	635
200	0	0	855
250	1	0	1067
300	1	0	1276
350	2	-1	1489
400	3	-1	1702
450	3	-2	1915
500	3	-2	2125
0	0	0	0
-12.5	0	0	-52
-25	0	0	-105
-37.5	0	0	-158
-50	0	0	-212
-60	0	0	-254
-70	0	0	-297
-80	0	0	-339
-90	-1	0	-381
-100	-1	0	-424
-125	-1	0	-529
-150	-1	0	-636

FIGURE 22

POSITIVE LIFT CALIBRATION CURVE



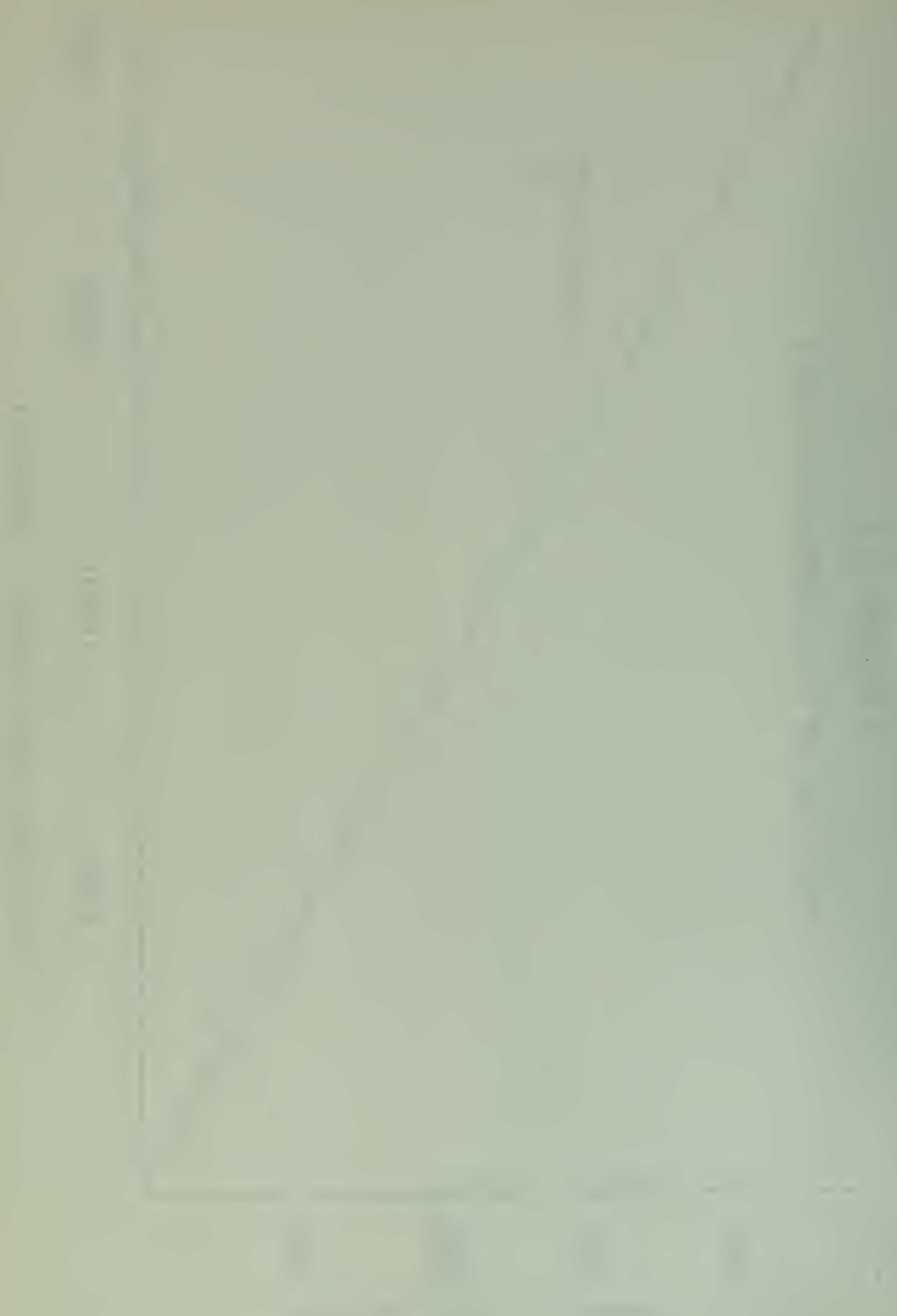
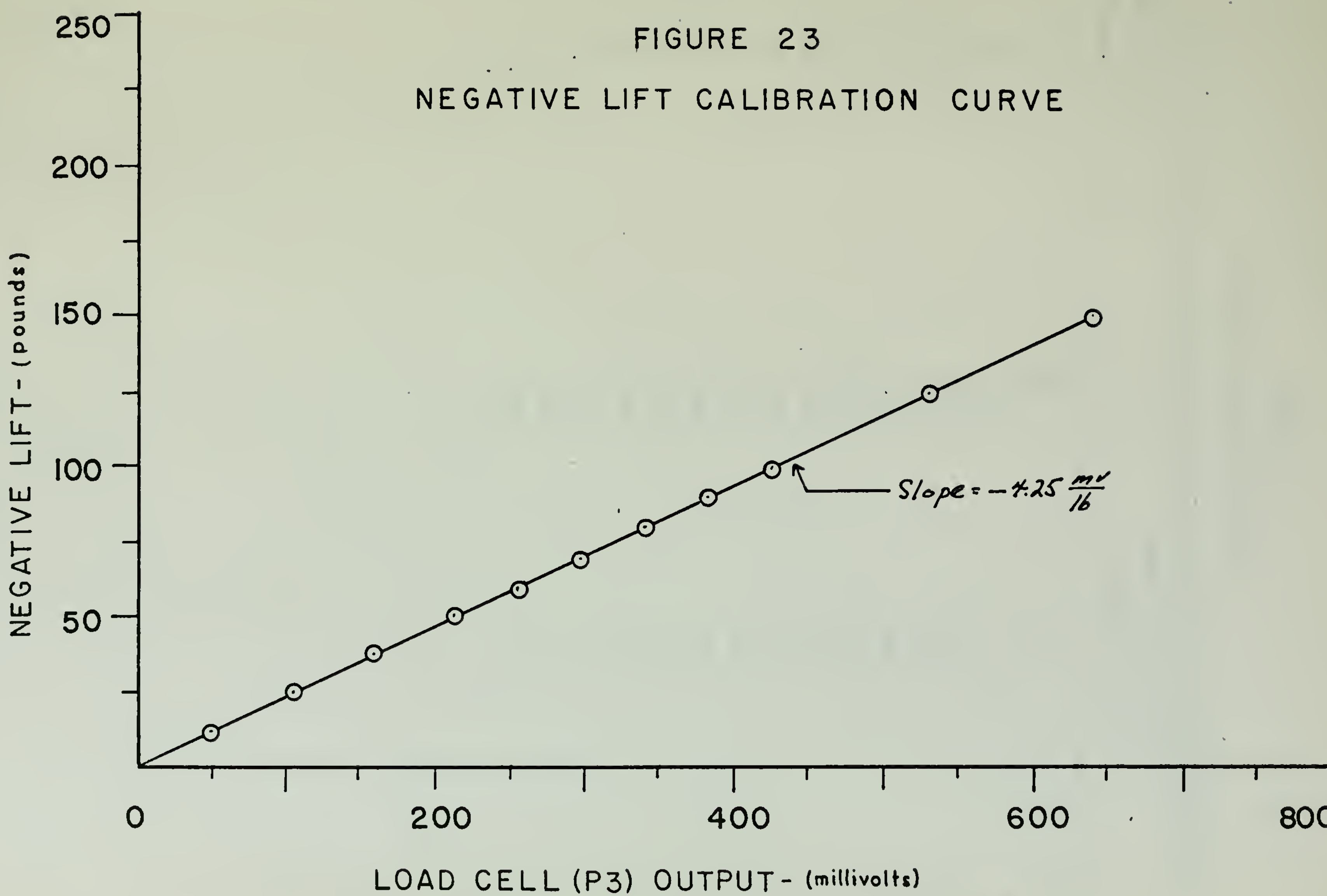


FIGURE 23

NEGATIVE LIFT CALIBRATION CURVE



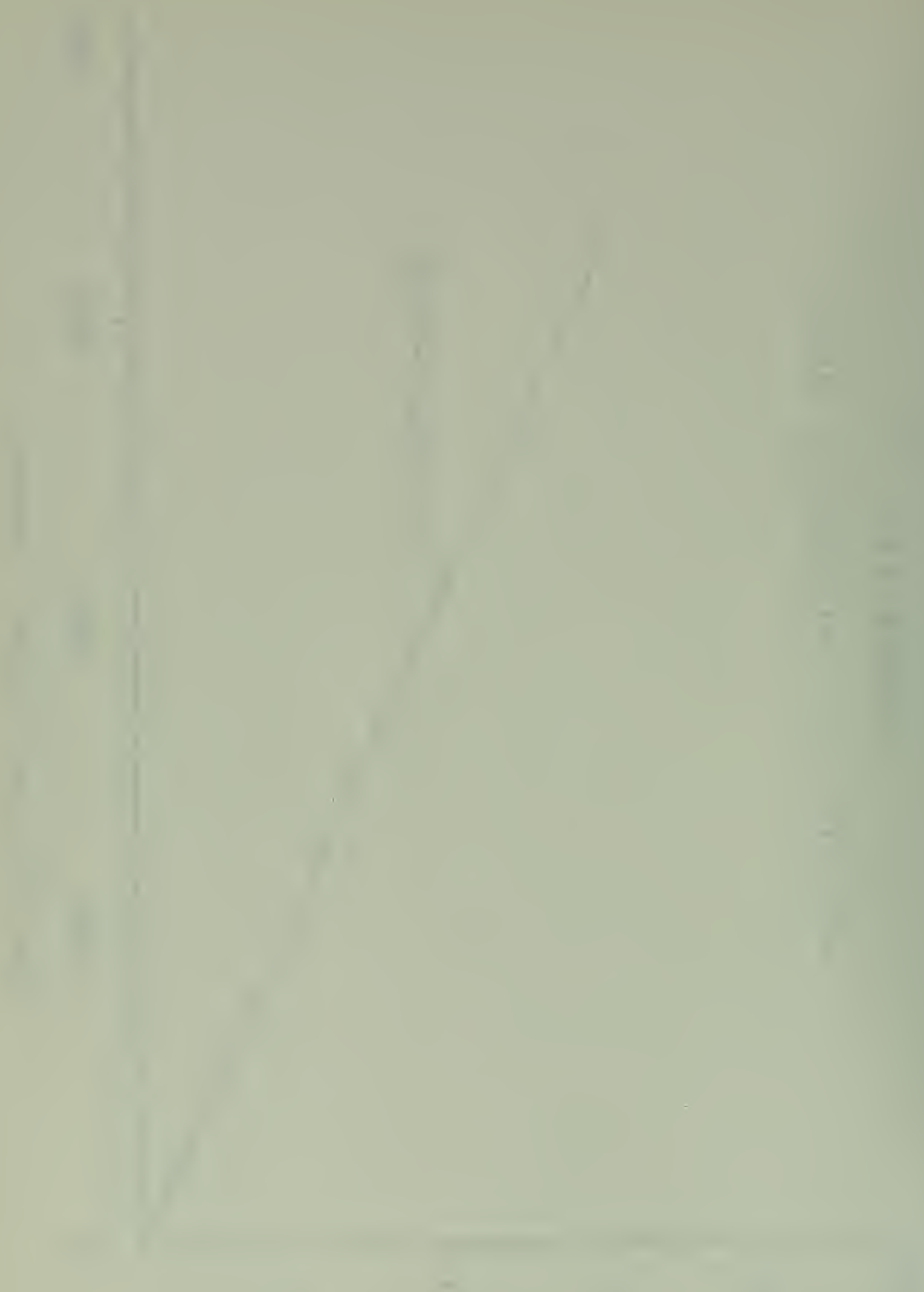


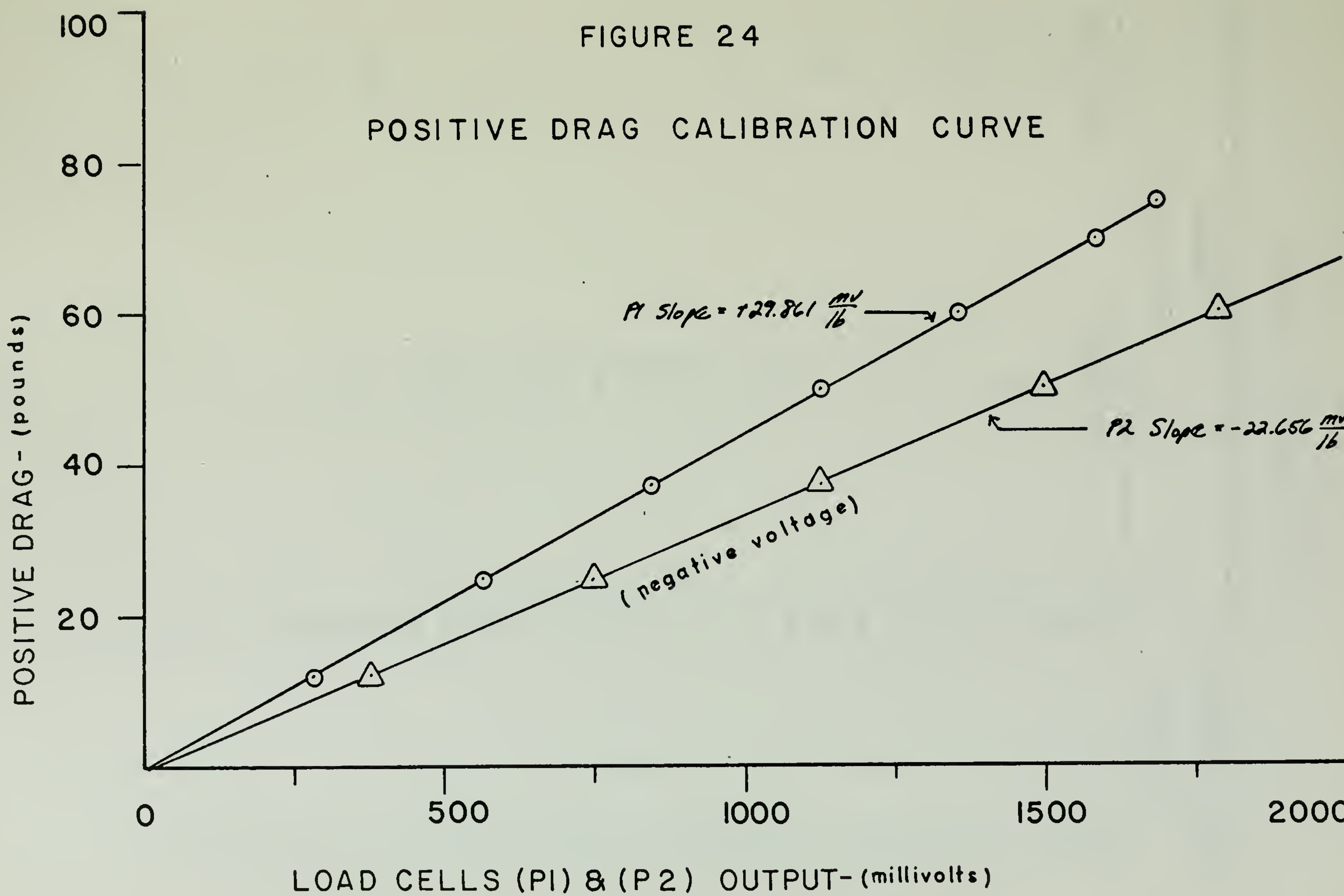
TABLE II

DRAG CALIBRATION DATA

DRAG LOAD Pounds	LOAD CELL OUTPUT Millivolts		
	P_1	P_2	P_3
0	0	0	0
12.5	375	-282	0
25	751	-565	0
37.5	1125	-849	0
50	1497	-1132	0
60	1792	-1357	0
70	2087	-1582	0
75	2235	-1696	-1
70	2098	-1591	0
60	1802	-1365	0
50	1508	-1140	0
37.5	1132	-854	0
25	756	-571	0
12.5	379	-285	0
0	0	0	0

FIGURE 24

POSITIVE DRAG CALIBRATION CURVE



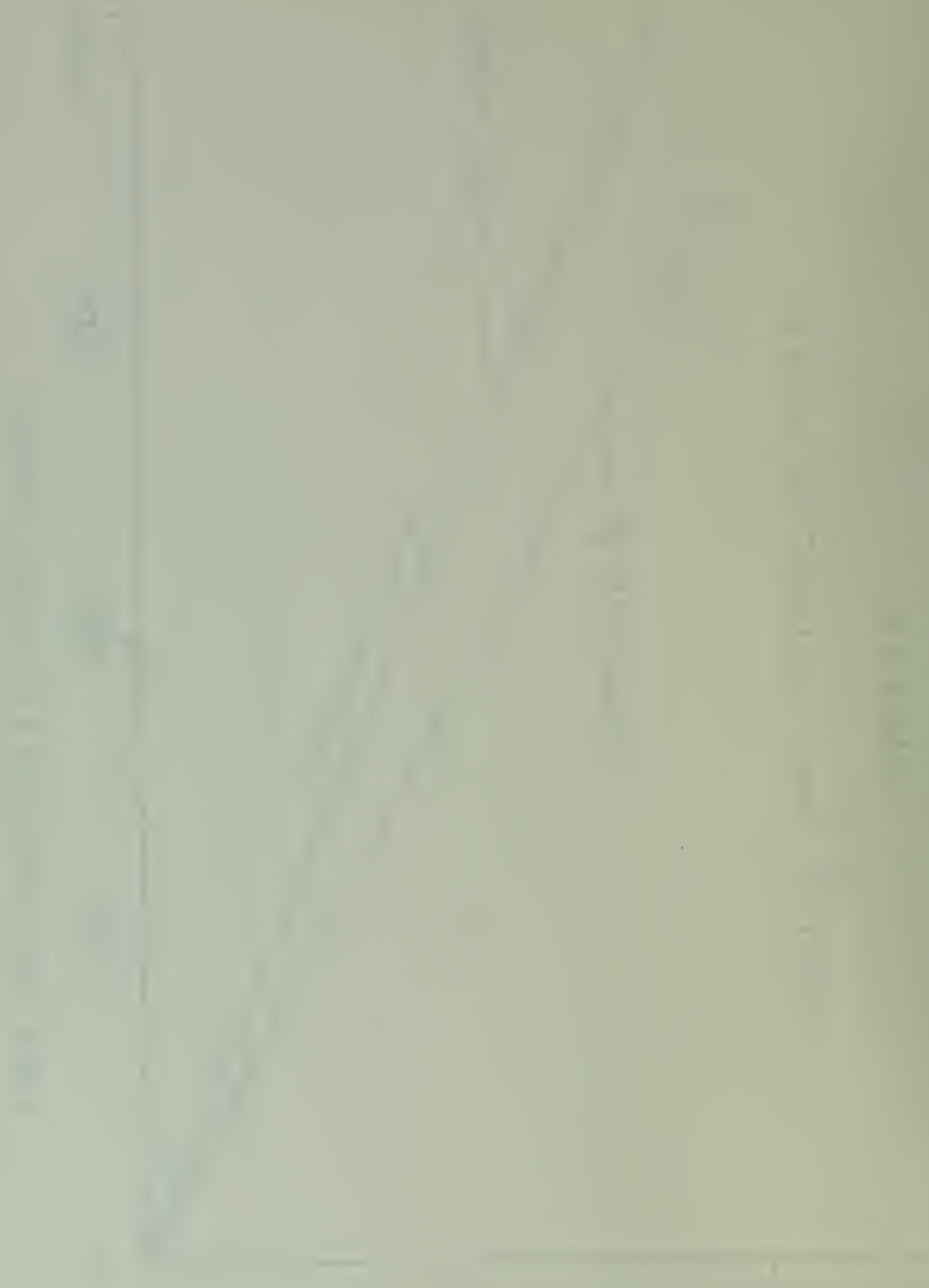


TABLE III

MOMENT CALIBRATION DATA

MOMENT Inch-Pounds		LOAD CELL OUTPUT Millivolts	
2 inch arm	4 inch arm	P_1	P_2
0		0	0
	0	0	0
25		12	-18
50		24	-36
	50	24	-36
75		36	-55
100		48	-73
	100	49	-73
120		58	-88
	150	74	-110
	200	98	-147
	240	118	-177
	400	196	-292
	800	391	-586
	900	445	-657
	240	118	-176
	200	98	-147
	150	74	-110
100		48	-73
	100	49	-73
57		36	-55
50		24	-36
	50	25	-36
25		12	-18
0		0	0
	0	0	0
0		0	0
	0	0	0

TABLE III (continued)

2 inch arm	4 inch arm	P_1	P_2
-25		-11	18
-50		-24	36
	-50	-24	36
-75		-36	54
-100		-48	73
	-100	-49	72
-120		-58	87
	-150	-74	109
	-200	-98	146
	-240	-119	175
	-400	-196	291
	-800	-391	585
	-900	-444	656
	-240	-119	175
	-200	-98	146
	-150	-74	109
-100		-48	73
	-100	-49	72
-75		-36	54
-50		-24	36
	-50	-25	36
-25		-11	18
0		0	0
	0	0	0

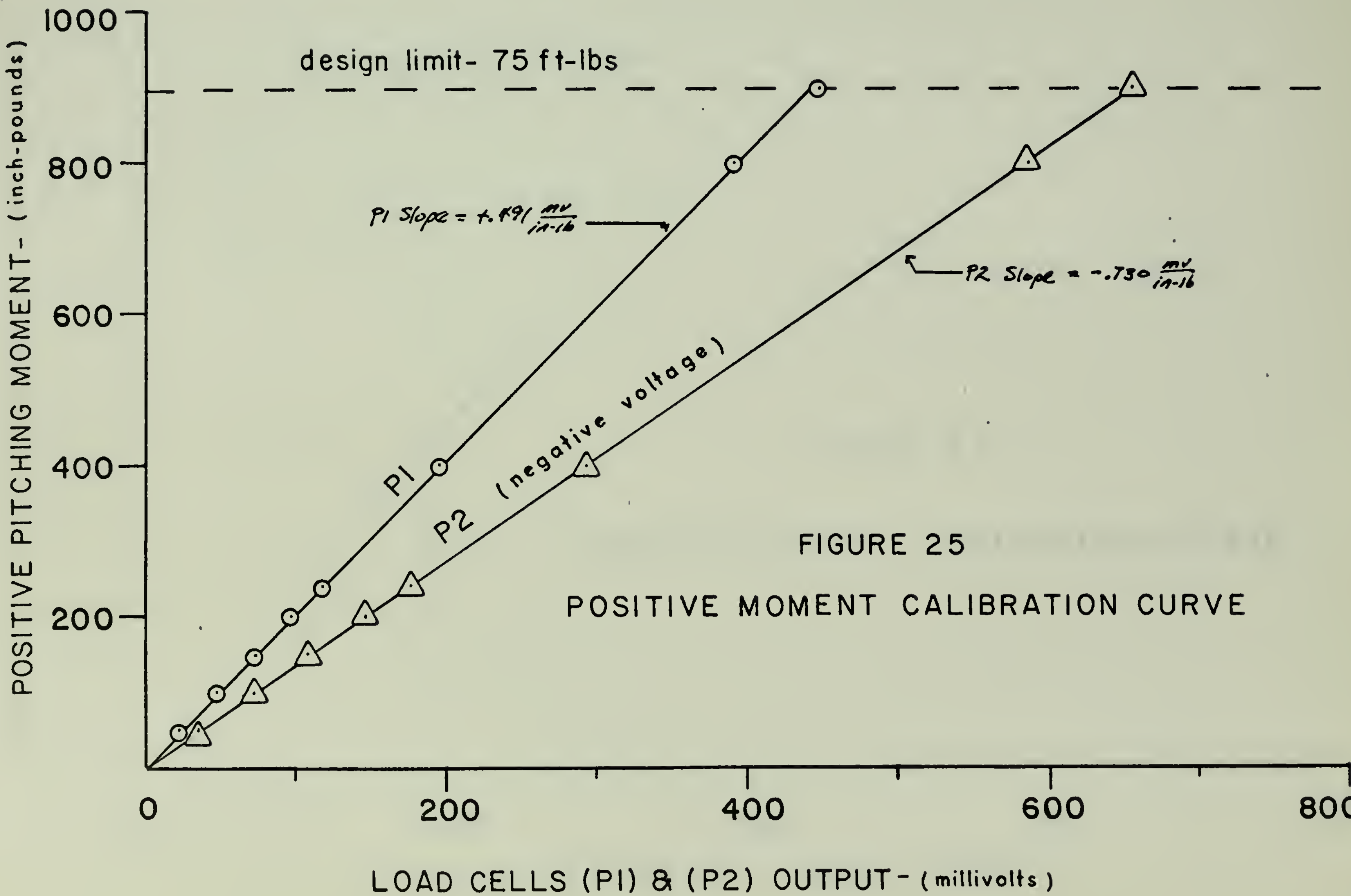


FIGURE 25

POSITIVE MOMENT CALIBRATION CURVE

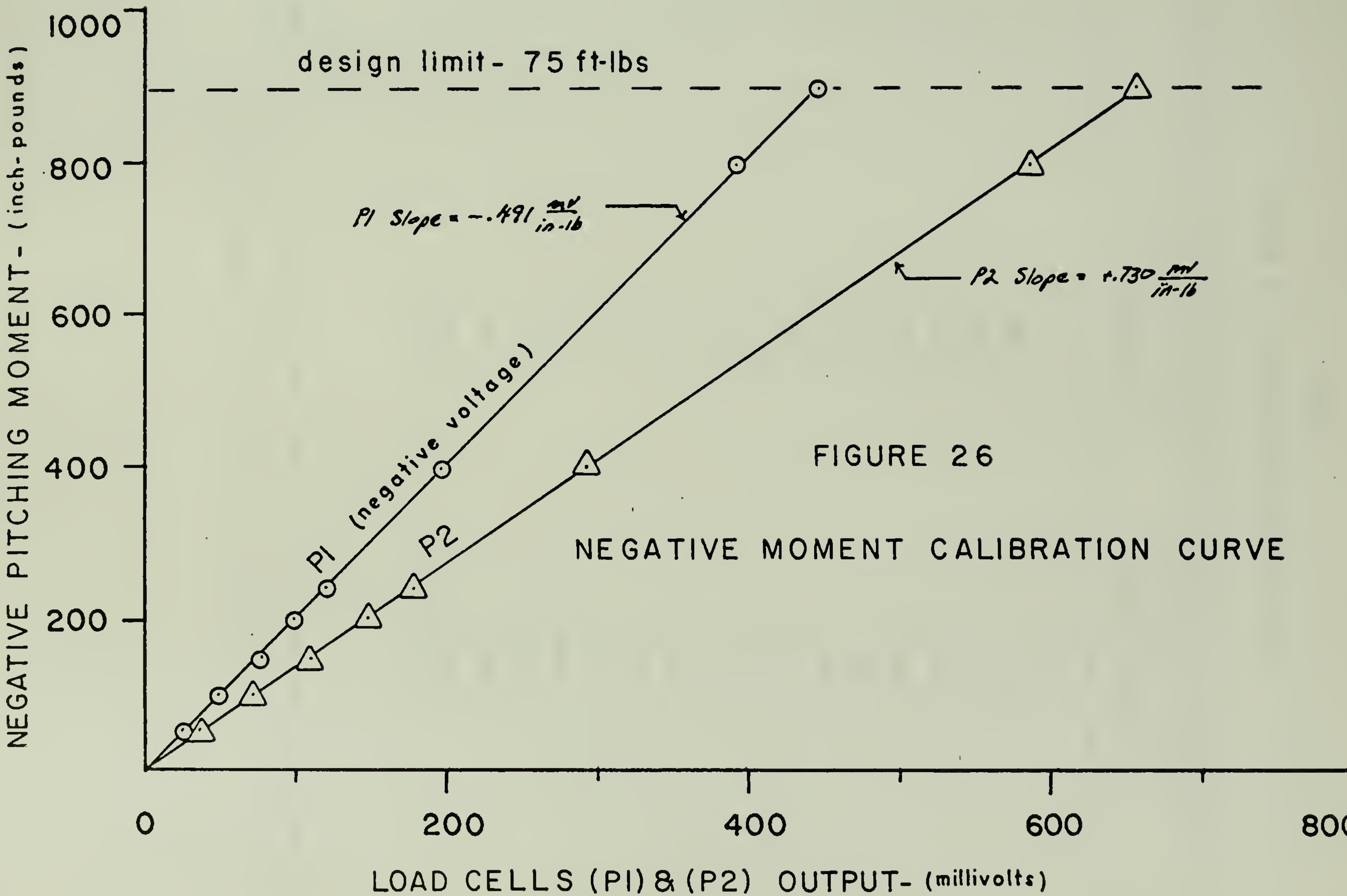


FIGURE 26

NEGATIVE MOMENT CALIBRATION CURVE

TABLE IV

ANGLE OF ATTACK CALIBRATION DATA

ANGLE OF ATTACK Degrees	TRANSDUCER OUTPUT Millivolts
	P_4
36^{o} *	74
35^{o}	126
30^{o}	371
25^{o}	590
20^{o}	786
15^{o}	984
10^{o}	1160
5^{o}	1335
0^{o}	1493
-5^{o}	1643
-10^{o}	1784
-15^{o}	1920
-20^{o}	2050
-25^{o}	2175
-30^{o}	2290
-35^{o}	2398
-36^{o} *	2420

*Note: $\pm 36^{o}$ is the physical limit of the AOA rotary rheostat; larger angles will ruin the transducer.

FIGURE 27
ANGLE OF ATTACK CALIBRATION CURVE

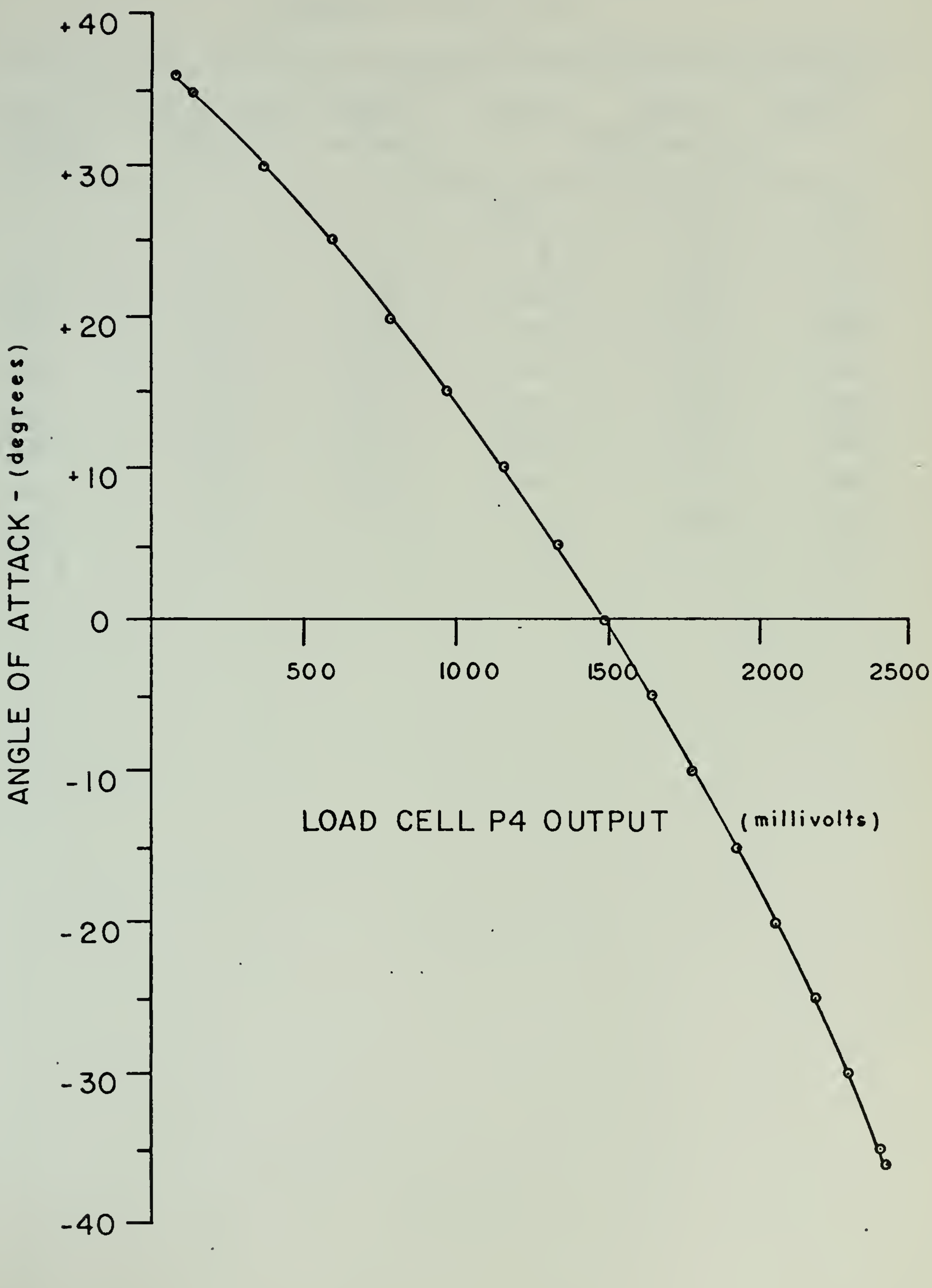


TABLE V

COMBINED LOADING DATA

LIFT LOAD Pounds	DRAG LOAD Pounds	MOMENT In-lbs	LOAD	CELL Millivolts	OUTPUT
			P_1	P_2	P_3
0	0	0	0	0	0
-12.5	10	-50	289	-207	-52
-25	20	-100	578	-417	-106
-37.5	30	-150	865	-625	-159
-50	40	-200	1152	-833	-213
-37.5	30	-150	868	-627	-159
-25	20	-100	582	-419	-106
-12.5	10	-50	291	-209	-52
0	0	0	0	0	0

VI. CONCLUSIONS

A. ALIGNMENT ACCURACY

The balance alignment described in Section III provided an accurate orientation for the flexures of the internal mechanism. The proper alignment of the flexures was required primarily to transmit restraint forces along the flexure axes, thus preventing damage to the flexure webs. The vertical alignment of the primary support was necessary in order to accurately resolve an applied load into its independent components of lift, drag and pitching moment. This alignment was in fact very accurate due to the careful levelling of the balance and transit as well as the use of significant colinear points to ascertain the necessary orientations. Once the balance was aligned by use of the transit, the most readily available crosscheck as to the resolution capability of the balance was to apply independent loadings of moment, lift and drag and observe data channels for indications of coupled output.

If the primary support was vertical, then a pure lift load applied to the balance would create an output only on the lift data channel. Any output on the drag channels would be evidence that the column was not vertical and consequently the vertically applied load was being resolved such that it produced a drag component directly proportional to the angular misalignment of the primary support, as well as creating a moment about the bottom anchor point of the lift

restraint flexure. By the same reasoning, an isolated drag load would produce some output on the lift channel that was proportional to that angular misalignment. Positive and negative moments of the same absolute value should produce output voltages of the same absolute magnitude. An additional method of cross checking the primary support alignment by means of applied pitching moments consisted of examining equal moments created by suspension from different moment arms. If the center of the calibration bar did not lie directly above the axis of the lift restraint flexure, the moment output channels would show different values for a given moment depending on whether the weights were suspended from a two or four inch moment arm. Because of the above considerations, an initial moment calibration should be made after the balance is aligned. This is a relatively simple process since it requires no auxiliary framework to apply the loads. Any minor adjustment that is required in order to produce consistent moment output signals must be made by changing the lengths of the two horizontal restraint flexures utilizing their adjustable ends. The top restraint flexure will change the angle that the lift restraint flexure makes with the vertical, since the bottom of the vertical flexure is anchored outside the main column. The bottom horizontal restraint flexure will change the horizontal location of the mounting eyes of the span supports. Once the initial moment calibration is satisfactory, the complete procedure can be carried out with a high degree of confidence

that the balance is correctly aligned.

B. DATA ANALYSIS

The graphical presentation of calibration data contained in Section V illustrates the fact that the load cell output is linear within the design load ranges of the balance. A least squares fit for all applicable data was conducted by use of a computer program which is described in detail in Appendix B. The results of this program confirm the graphical evidence of balance linearity. The only exception to this is the angle of attack transducer; however, since this variable is an independent factor, it has no effect on force resuolution by the balance. In addition, a least squares second order polynomial approximation of the transducer output produced a very accurate representation of the angle of attack calibration curve. The maximum error between the two curves was less than one percent:

P_4	α CAL DATA	α LEAST SQUARES	α ERROR
(1160 mv)	(10.0 deg.)	(10.09 deg.)	(.0925 deg.)

The vibrator motor made very little difference in output signals. This indicated the virtual absence of mechanical hysteresis in the balance. The calibration of the balance does utilize the data acquired with the vibrator on, because in each case it was slightly more exact as applied to linear output.

The calibration data for lift, drag and moment were also

analyzed for deviation from computed mean values. The results appear in the output of the data analysis computer program as standard deviations for each load cell under the three conditions of independent loading. A correlation of these deviations produces the following results:

DRAG

$$\{\sigma_P\}_{DRAG} = \begin{Bmatrix} \sigma_{P1} \\ \sigma_{P2} \end{Bmatrix} = \begin{Bmatrix} 7.1 \\ 3.55 \end{Bmatrix}$$

Utilizing the balance output matrix for determination of drag:

$$\sigma_{DRAG} = (.0684)\sigma_{P1} + (.046)\sigma_{P2} = .649 \text{ lbs}$$

MOMENT

$$\{\sigma_P\}_{MOMENT} = \begin{Bmatrix} \sigma_{P1} \\ \sigma_{P2} \end{Bmatrix} = \begin{Bmatrix} .865 \\ .621 \end{Bmatrix}$$

$$\sigma_{MOMENT} = (2.122)\sigma_{P1} + (-2.797)\sigma_{P2} = -3.572 \text{ in-lbs}$$

LIFT

$$\{\sigma_P\}_{LIFT} = \{\sigma_{P3}\} = \{1.69\}$$

$$\sigma_{LIFT} = (.235)\sigma_{P3} = .397 \text{ lbs}$$

For typical test conditions, $S = 3 \text{ ft}^2$, $\bar{c} = .75$ ft, $q = 20 \text{ lb/ft}^2$; therefore,

$$\sigma_{C_D} = \frac{(.649 \text{ lbs})}{(20 \text{ lb/ft}^2)(3 \text{ ft}^2)} = .0108$$

$$\sigma_{C_M} = \frac{(-3.572 \text{ in-lb})}{(20 \text{ lb/ft}^2)(.75 \text{ ft})(3 \text{ ft}^2)(12 \text{ in/ft})} = -.0066$$

$$\sigma_{C_L} = \frac{(.397 \text{ lbs})}{(20 \text{ lb/ft}^2)(3 \text{ ft}^2)} = .0066$$

The output matrix calculated a loading vector that had the values of the independent loads computed accurately. However, unacceptable values for pitching moment were produced from an independent drag load as well as slight amounts of drag from a pure moment application. These aberrations are displayed in the output section of the data analysis computer program. They were a direct result of the transformation matrix coupling all deviations in horizontal load cell signals and apportioning the deviations erroneously. The primary cause of such distribution is the fact that the voltage full scale range for drag was an order of magnitude greater than that for pitching moment. Since the balance-computed loading vector is the product of a linear system, the computational errors committed through the use of the output matrix can be analyzed by the principle of superposition:

$$\{F + \Delta F\} = [T]\{P + \Delta P\} \qquad \{F\} = [T]\{\Delta P\}$$

$$\begin{Bmatrix} \Delta M \\ \Delta D \\ \Delta L \end{Bmatrix} = \begin{bmatrix} -2.122 & -2.797 & 0 \\ .0684 & .046 & 0 \\ 0 & 0 & .235 \end{bmatrix} \begin{Bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \end{Bmatrix}$$

$$\Delta M(\text{in-lbs}) = -2.122 \Delta P_1 - 2.797 \Delta P_2$$

$$\Delta D(\text{lbs}) = .0684 \Delta P_1 + .046 \Delta P_2$$

It is clear that small errors in signals P_1 and P_2 will cause unacceptable error probabilities. A standard deviation in drag coefficient of .0108 is of the same order as the profile drag of a test model. Obviously, a standard deviation

in pitching moment of over three inch-pounds is excessive for the purposes of model testing. In its present configuration, the balance could not resolve combined loading conditions of drag and moment; the drag resolution was reasonable but the moment measure was not:

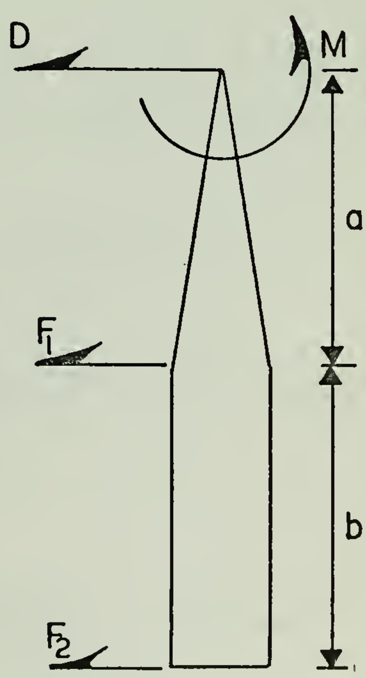
COMBINED LOAD	OUTPUT	BALANCE RESOLUTION
M = -200 in-lbs	P_1 = 1152 mv	M = -114.7 in-lbs
D = +40 lbs	P_2 = -833 mv	D = +40.46 lbs

C. RECOMMENDATIONS

As stated previously, the primary reason for the failure of the balance to resolve combined loadings of moment and drag is the scale range differences in load cell output between drag and moment loadings. The cause of the scale range incompatibility is the length of the span support struts:

$$F_1 + F_2 + D = 0$$

$$-F_1 a - F_2(a + b) + M = 0$$



solving for restraint forces:

$$F_1 = -\frac{1}{b}\left[D(a + b) - M\right]$$

$$F_2 = \frac{1}{b}(Da + M)$$

If length a is decreased the relative magnitude of the moment and drag contributions to the restraint forces become more compatible. However, the practicality of such a modification is limited by the necessity of having struts that are long enough to suspend a model in a tunnel test section.

APPENDIX A

LOAD CELL DESIGN AND SPECIFICATION

GENERAL

After considering the geometric restrictions of the linkages comprising the internal balance mechanism as well as the desired load measurement accuracy, the primary specifications for the load cells were established. These parameters were a maximum dimension of three inches along the major axis of each cell and a maximum allowable deflection range of plus or minus eight thousandths of one inch. All remaining dimensions except the web thickness were derived from similar practical considerations. Aluminum was chosen for compatibility with existing balance construction.

STATIC ANALYSIS

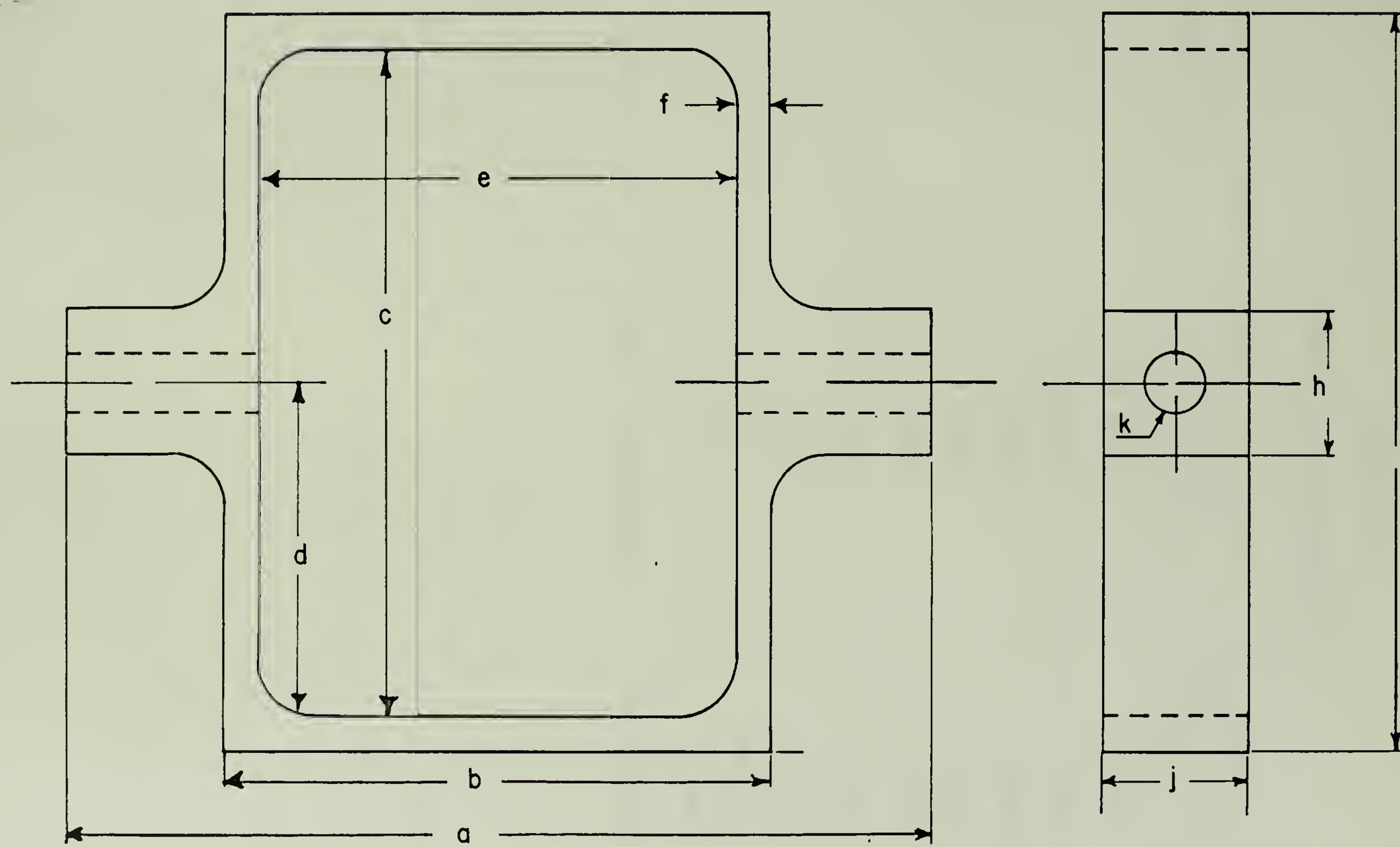
Consider a load cell as an indeterminant structure composed of two sets of identical components as shown in figure (29):

The moment function in Piece 1 can be expressed as $M(x) = (M - Px)$;

By the theorem of Castigliano, the elastic strain energy stored in component 1 is:

$$U = 2\left\{\frac{1}{2EI_1}\int_0^{\frac{1}{2}(\ell-d)}\left(M-\frac{P}{2}x\right)^2 dx + \frac{1}{2EI_2}\int_{\frac{1}{2}(\ell-d)}^{\ell/2}\left(M-\frac{P}{2}x\right)^2 dx\right\}$$

Since $I_2 \gg I_1$, the total elastic energy stored can be approximated by



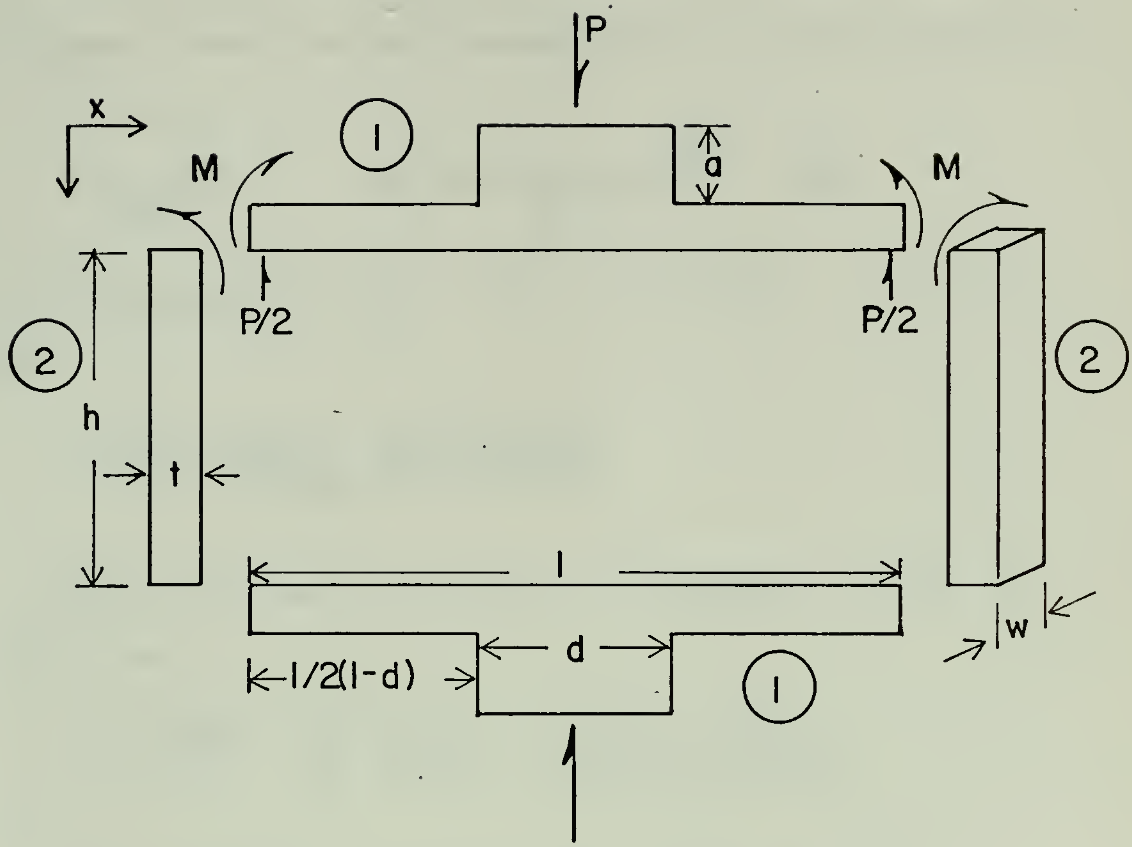
LOAD CELL STRUCTURE

FIGURE 28

TABLE VI

LOAD CELL DIMENSIONS

DIMENSION	50 LB LOAD CELL	140 LB LOAD CELLS
a	3.00"	3.00"
b	1.882"	1.98"
c	2.280"	2.280"
d	1.140"	1.140"
e	1.640"	1.640"
f	0.121"	0.170"
g	2.522"	2.620"
h	0.50"	0.50"
j	0.495"	0.495"
k	10-32 clearance	10-32 clearance



LOAD CELL STATICS

FIGURE 29

(1) $$U = \frac{1}{EI_1}\int_0^{\frac{1}{2}(\ell-d)} \left(M - \tfrac{P}{2}x\right)^2 dx$$

$$\frac{\partial U}{\partial M} = 2\theta_1 (x{=}0) = \frac{2}{EI_1}\int_0^{\frac{1}{2}(\ell-d)} \left(M - \tfrac{P}{2}x\right) dx = \frac{(\ell-d)}{EI_1}\left[M - \frac{P}{8}(\ell-d)\right]$$

The moment function for component 2 is a constant value, M;

$$U = \frac{1}{2EI_1}\int_0^h M^2 dx \qquad 2\theta_2 (x{=}0) = \frac{\partial U}{\partial M} = \frac{1}{EI_1}\int_0^h M dx = \frac{Mh}{EI_1}$$

for compatibility, $\theta_1 = -\theta_2$; therefore

(2)

$$M = \frac{P\ell}{8}\,\frac{(1-d/\ell)}{1 + h/\ell \frac{1}{(1-d/\ell)}} = \frac{P\ell^2(1-d/\ell)^2}{8[h + \ell(1-d/\ell)]}$$

The stress on the surfaces of component 2 can be calculated:

$$\sigma = \frac{M(t/2)}{I_1}; \quad \frac{\sigma}{P} = \left(\frac{M}{P}\right)\frac{t}{2I_1} = \left(\frac{\ell^3 t}{16 I_1}\right)\frac{(1-d/\ell)^2}{[h + \ell(1-d/\ell)]}$$

For aluminum, $E_1 = E_2 = E$; $E = \frac{\sigma}{\epsilon} = 10^7 \frac{lb}{in^2}$ $\frac{\epsilon}{P} = \frac{\sigma}{P} \times 10^{-7}$

(3)

$$\frac{\epsilon}{P}\left(\mu \frac{in/in}{lb}\right) = .1\frac{\sigma}{P} = \left(\frac{\ell^3 t}{160 I}\right)\frac{(1-d/\ell)^2}{[h + \ell(1-d/\ell)]}$$

APPLICATION

The difference between the fifty pound load cell and the one hundred pound load cells is reduced to a required variation in web thickness in order to limit the

resultant deflection due to maximum applied load.

For one hundred forty lb cell:

Deflection of component (1) at point of load application is

$$\Delta k_p = \frac{\partial U}{\partial P} = \frac{2}{EI}\int_0^{\frac{1}{2}(\ell-d)} (-x/2)\left(M - \frac{P}{2}x\right)dx = -\frac{(\ell-d)^2}{2EI}\left[M - \frac{P}{6}(\ell-d)\right]$$

The total deflection of the cell along the load application axis is twice this value

$$\Sigma\Delta k_p = -\frac{(\ell-d)^2}{EI}\left[M - \frac{P}{6}(\ell-d)\right]$$

substituting the moment, equation (2)

$$\Sigma\Delta k_p = \left(\frac{P}{48EI}\right)\left\{\frac{\ell^3(1-d/\ell)^3}{[h+\ell(1-d/\ell)]}\left[4h+3\ell(1-d/\ell)\right]\right\}$$

To calculate the minimum web thickness t:

$$I = \frac{wt^3}{12} \qquad t^3 = \frac{12I}{w}$$

$$t^3 = \left(\frac{P}{4wE\Delta k_p}\right)\left\{\frac{\ell^3(1-d/\ell)^3}{[h+\ell(1-d/\ell)]}\left[4h+3\ell(1-d/\ell)\right]\right\}$$

using the approximated dimensions

ℓ = 2.4 inches   h = 1.7 inches

d = .50 inches $\Sigma\Delta k_p = 16 \times 10^{-3}$ inches at 140 lbs load

w = .495 inches

$d/\ell = \frac{.5}{2.4} = .20833 \quad (1 - d/\ell) = .791666 \quad \ell(1 - d/\ell) = 1.9$

$\ell^3 (1 - d/\ell)^3 = 6.859 \qquad h + \ell(1 - d/\ell) = 10.459$

$$t^3 = \frac{140}{(4)(.495)(10^7)(16 \times 10^{-3})} \quad \frac{6.859\ (12.5)}{10.459} =$$

$(4.4192 \times 10^{-4})\ (8.19748) = 3.62263 \times 10^{-3})$

$t \geq \boxed{.154 \text{ inches}}$

For an actual web thickness of .170 inches, the use of equation (3) gives the output voltage rates for the load cell connected to a balanced bridge circuit:

$$\frac{\epsilon}{P} = \frac{\ell^3 t}{160 I} \frac{(1 - d/\ell)^2}{\left[h+\ell(1-d/\ell)\right]} \qquad I = \frac{wt^3}{12} = \frac{(.495)(3.62263)}{12} \times 10^{-3} =$$

$1.494334 \times 10^{-4}\ in^4$

$$\frac{\epsilon}{P} = \left[\frac{(2.62)^3\ (.170)}{(160)(1.4943)} \times 10^4\right] \left\{\frac{.6547}{(1.98 + 2.119)}\right\} = 20.42 \mu \frac{in/in}{lb} =$$

2859 mv at 140 lbs

The strain gauges were mounted on the side components 2 of the load cells because the moment along these members does not vary with strain gauge positioning.

For an excitation voltage of 5 volts DC and a gauge factor of 2.0, 1000μ in/in. = 10 MV output from a balanced bridge circuit.

$$\frac{\epsilon}{P} \times P_{max} = 20.42\ \mu \frac{in/in}{lb} \times 140 \text{ lbs} = 2859 \text{ MV maximum range;}$$

this agrees closely with calibration values.

APPENDIX B

DATA ANALYSIS COMPUTER PROGRAM

GENERAL

All data analysis was carried out through a FORTRAN IV program utilizing the Naval Postgraduate School IBM 360/67 digital computer. The primary impetus for computer analysis resulted from the necessity to obtain accurate slope values from the various load cell calibration curves. Although reasonable results could be obtained by graphical methods, more precise information was available through the use of a least squares fit.

An initial graphical plot of calibration data showed the balance output to be linear with respect to independent loading conditions; consequently, the least squares fit of data for each load cell was assumed to conform to a first order polynomial of the form $y = ax + b$ where (a) represents the slope of the particular calibration curve and (b) the intercept of the curve along the ordinate.

Calibration data for the angle of attack transducer necessitated the use of a higher order polynomial. The most functional solution to this problem was to use a packaged subroutine to calculate the coefficients of a fourth order polynomial, since a trial procedure indicated a good fit for such an order. It was estimated that an acceptable accurate expression for the model angle of attack could be produced by this method.

PROGRAM DETAILS

All calibration data was arranged to be read in as a matrix INPUT (102,5) arranged in an easily accessible pattern as follows:

1	1	2	3	4	5
52	MOMENT LOADS	P_1	P_2	NULL	NULL
67	DRAG LOADS	P_1	P_2	NULL	NULL
85	LIFT LOADS	NULL		P_3	NULL
102	AOA	NULL		NULL	P_4

Two original subroutines COMP1 and COMP2 were used to compute least squares first order polynomials for applicable load cells under independent conditions of moment, drag or lift loadings. COMP2 is used only for analyzing lift data and is a necessity in order to avoid cumbersome linkage problems with the main program. The resultant slopes and intercepts are stored in matrices COEFF (3,3) and INCPT (3,3) for further processing. The format and information contained in these matrices is readily discernible from the form of the offline printer output.

Once these steps have been completed, the main program produces the balance output matrix TRANS (3,3). The development and purpose of this matrix was discussed in detail in Section III. TRANS (3,3) is utilized by a third original

subroutine, COMP3.

COMP3 performs three major operations on the calibration data for moment, drag and lift. First, COEFF (3,3) is used to calculate the mean values of load cell output in millivolts for each value of independent variable available. The second operation performed is the subtraction of these mean values from the actual calibration values in order to obtain a standard deviation for each load cell under each applicable loading condition. The standard deviations, expressed in units of millivolts, are stored in matrix SIGMA (3,3) for output purposes. The final operation of COMP3 is to multiple the actual calibration values of load cell output by the output matrix in order to obtain the calculated loading conditions that would be produced by the balance. These computed loadings are stored as actual values in matrix ACTVL.

A prepackaged subrouting LSQPL2 was used to evaluate the coefficients of the fourth order polynomial that expresses angle of attack as a function of transducer voltage. Some of the printed output from this subroutine was supressed for brevity and clarity.

The printed output from the data analysis program arranges all calculated and indexing information in convenient reference form. The program listing contains adequate comment to enable the interested reader to follow the sequence of events contained in the program.

MOMENT DATA ANALYSIS

COMPARATIVE OUTPUTS

COMPUTED LOADING

MOMENT	P1(MV)		P2(MV)		MOMENT	DRAG
(IN-LBS)	DATA	MEAN	DATA	MEAN	(IN-LBS)	(LBS)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
25.0	12.000	12.282	-18.000	-18.261	24.869	-0.007
50.0	24.000	24.564	-36.000	-36.522	49.737	-0.015
75.0	36.000	36.846	-55.000	-54.783	77.401	-0.068
100.0	48.000	49.128	-73.000	-73.044	102.270	-0.075
120.0	58.000	58.954	-88.000	-87.653	122.994	-0.081
100.0	48.000	49.128	-73.000	-73.044	102.270	-0.075
75.0	36.000	36.846	-55.000	-54.783	77.401	-0.068
50.0	24.000	24.564	-36.000	-36.522	49.737	-0.015
25.0	12.000	12.282	-18.000	-18.261	24.869	-0.007
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
50.0	24.000	24.564	-36.000	-36.522	49.737	-0.015
100.0	49.000	49.128	-73.000	-73.044	100.149	-0.007
150.0	74.000	73.693	-110.000	-109.566	150.560	0.001
200.0	98.000	98.257	-147.000	-146.089	203.093	-0.059
240.0	118.000	117.908	-177.000	-175.306	244.541	-0.072
400.0	196.000	196.514	-292.000	-292.177	400.595	-0.027
800.0	391.000	393.028	-586.000	-584.354	808.903	-0.214
900.0	445.000	442.156	-657.000	-657.398	892.854	0.213
240.0	118.000	117.908	-176.000	-175.306	241.745	-0.026
200.0	98.000	98.257	-147.000	-146.089	203.093	-0.059
150.0	74.000	73.693	-110.000	-109.566	150.560	0.001
100.0	49.000	49.128	-73.000	-73.044	100.149	-0.007
50.0	25.000	24.564	-36.000	-36.522	47.616	0.054
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
-25.0	-11.000	-12.282	18.000	18.261	-26.990	0.076
-50.0	-24.000	-24.564	36.000	36.522	-49.737	0.015
-75.0	-36.000	-36.846	54.000	54.783	-74.606	0.022
-100.0	-48.000	-49.128	73.000	73.044	-102.270	0.075
-120.0	-58.000	-58.954	87.000	87.653	-120.198	0.035

-100.0	-48.000	-49.128	73.000	73.044	-102.270	0.075
-75.0	-36.000	-36.846	54.000	54.783	-74.606	0.022
-50.0	-24.000	-24.564	36.000	36.522	-49.737	0.015
-25.0	-11.000	-12.282	18.000	18.261	-26.990	0.076
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
-50.0	-24.000	-24.564	36.000	36.522	-49.737	0.015
-100.0	-49.000	-49.128	72.000	73.044	-97.353	-0.039
-150.0	-74.000	-73.693	109.000	109.566	-147.765	-0.047
-200.0	-98.000	-98.257	146.000	146.089	-200.298	0.014
-240.0	-119.000	-117.908	175.000	175.306	-236.828	-0.089
-400.0	-196.000	-196.514	291.000	292.177	-397.800	-0.019
-800.0	-391.000	-393.028	585.000	584.354	-806.107	0.168
-900.0	-444.000	-442.156	656.000	657.398	-892.180	-0.190
-240.0	-119.000	-117.908	175.000	175.306	-236.828	-0.089
-200.0	-98.000	-98.257	146.900	146.089	-202.814	0.055
-150.0	-74.000	-73.693	109.000	109.566	-147.765	-0.047
-100.0	-49.000	-49.128	72.000	73.044	-97.353	-0.039
-50.0	-25.000	-24.564	36.000	36.522	-47.616	-0.054
0.0	0.0	0.0	0.0	0.0	0.0	0.0

DRAG DATA ANALYSIS

COMPARATIVE OUTPUTS | COMPUTED LOADING

DRAG (LBS)	P1(MV) DATA	P1(MV) MEAN	P2(MV) DATA	P2(MV) MEAN	MOMENT (IN-LBS)	DRAG (LBS)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	375.000	373.262	-282.000	-283.201	-7.045	12.674
25.0	751.000	746.525	-565.000	-566.403	-13.415	25.371
37.5	1125.000	1119.787	-849.000	-849.605	-12.747	37.884
50.0	1497.000	1493.050	-1132.000	-1132.806	-10.633	50.307
60.0	1792.000	1791.659	-1357.000	-1359.368	-7.341	60.132
70.0	2087.000	2090.269	-1582.000	-1585.929	-4.047	69.957
75.0	2235.000	2239.574	-1696.000	-1699.209	0.730	74.835
70.0	2098.000	2090.269	-1591.000	-1585.929	-2.223	70.295
60.0	1802.000	1791.659	-1365.000	-1359.368	-6.187	60.448
50.0	1508.000	1493.050	-1140.000	-1132.806	-11.600	50.691
37.5	1132.000	1119.787	-854.000	-849.605	-13.617	38.133
25.0	756.000	746.525	-571.000	-566.403	-7.247	25.437
12.5	379.000	373.262	-285.000	-283.201	-7.142	12.810
0.0	0.0	0.0	0.0	0.0	0.0	0.0

LIFT DATA ANALYSIS

	COMPARATIVE OUTPUTS		COMPUTED LOAD
LIFT	P3(MV)		LIFT
(LBS)	DATA	MEAN	(LBS)
0.0	0.0	0.0	0.0
100.000	423.0000	425.0220	99.524
200.000	855.0000	850.0439	201.166
300.000	1276.0000	1275.0659	300.220
400.000	1702.0000	1700.0879	400.450
500.000	2125.0000	2125.1099	499.974
0.0	0.0	0.0	0.0
-12.500	-52.0000	-53.1277	-12.235
-25.000	-105.0000	-106.2555	-24.705
-37.500	-158.0000	-159.3832	-37.175
-50.000	-212.0000	-212.5110	-49.880
-60.000	-254.0000	-255.0132	-59.762
-70.000	-297.0000	-297.5154	-69.879
-80.000	-339.0000	-340.0176	-79.761
-90.000	-381.0000	-382.5198	-89.642
-100.000	-424.0000	-425.0220	-99.760
-125.000	-529.0000	-531.2773	-124.464
-150.000	-636.0000	-637.5330	-149.639

ANGLE OF ATTACK DATA ANALYSIS

COEFFICIENTS OF THE POWER SERIES EXPANSION

Y(X)=B(1)+B(2)*X+B(3)*X**2+B(4)*X**3+...

B(1)= 3.73903D 01   B(2)=-1.82433D-02   B(3)=-5.26347D-06   B(4)= 1.01468D-09

ESTIMATES OF ERROR FOR THE COEFFICIENTS

ERRB(1)=3.693D-01   ERRB(2)=2.332D-03   ERRB(3)=3.883D-06   ERRB(4)=2.328D-09

B(5)=-3.72775D-13

ERRB(5)=4.575D-13

I	X(I)	F2(I)	Y(I)	DELY(I)	WI(I)	WN(I)
1	2420.000	-3.6000000D 01	-3.5988028D 01	1.1972080D-02	1.0000D 00	5.882353D-02
2	2398.000	-3.5000000D 01	-3.4958796D 01	4.1204478D-02	1.0000D 00	5.882353D-02
3	2290.000	-3.0000000D 01	-3.0055149D 01	-5.5149124D-02	1.0000D 00	5.882353D-02
4	2175.000	-2.5000000D 01	-2.5090372D 01	-9.0372174D-02	1.0000D 00	5.882353D-02
5	2050.000	-2.0000000D 01	-1.9970072D 01	2.9928052D-02	1.0000D 00	5.882353D-02
6	1920.000	-1.5000000D 01	-1.4924035D 01	7.5964757D-02	1.0000D 00	5.882353D-02
7	1784.000	-1.0000000D 01	-9.9221988D 00	7.7801189D-02	1.0000D 00	5.882353D-02
8	1643.000	-5.0000000D 00	-5.0079301D 00	-7.9300713D-03	1.0000D 00	5.882353D-02
9	1493.000	0.0	-5.4754112D-02	-5.4754112D-02	1.0000D 00	5.882353D-02
10	1335.000	5.0000000D 00	4.8850367D 00	-1.1496334D-01	1.0000D 00	5.882353D-02
11	1160.000	1.0000000D 01	1.0054476D 01	5.4475963D-02	1.0000D 00	5.882353D-02
12	984.000	1.5000000D 01	1.4959847D 01	-4.0153337D-02	1.0000D 00	5.882353D-02
13	786.000	2.0000000D 01	2.0149820D 01	1.4981991D-01	1.0000D 00	5.882353D-02
14	590.000	2.5000000D 01	2.4957821D 01	-4.2179054D-02	1.0000D 00	5.882353D-02
15	371.000	3.0000000D 01	2.9942368D 01	-5.7631821D-02	1.0000D 00	5.882353D-02
16	126.000	3.5000000D 01	3.5010056D 01	1.0056465D-02	1.0000D 00	5.882353D-02
17	74.000	3.6000000D 01	3.6011910D 01	1.1910142D-02	1.0000D 00	5.882353D-02

DATA FITTING VALUES

	SLOPES			INTERCEPTS			STANDARD DEVIATIONS		
	M	D	L	M	D	L	M	D	L
P1	0.491	29.861	0.0	-0.039	-0.152	0.0	0.865	7.116	0.0
P2	-0.730	-22.656	0.0	-0.371	-0.045	0.0	0.621	3.546	0.0
P3	0.0	0.0	0.235	0.0	0.0	-0.246	0.0	0.0	1.690

```
C       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C       C                             C
C       C                             C
C       C    CATA REDUCTION PROGRAM   C
C       C                             C
C       C                             C
C       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C
C
C
        INTEGER*4 A,G
        REAL*4 MEAN,INPUT,INCPT,ACTVL
        REAL*8 X,F2,WI,Y,DELY,B,SB,TITLE
        DIMENSICN X(17),F2(17),WI(17),Y(17),CELY(17),
       XB(11),SB(11),COEFF(3,3),TRANS(3,3),SIG(3,3),
       XINCPT(3,3),INPUT(102,5),PCINTS(60,5),
       XMEAN(102,3),ACTVL(102,2)
        CCMMCN INPUT
C
C
C           CCCCCCCCCCCCCCCCCC
C           C                C
C           C   READ IN DATA C
C           C                C
C           CCCCCCCCCCCCCCCCCC
C
C
        DC 5 I=1,102
        READ (5,500) (INPUT(I,J),J=1,5)
5       CONTINUE
        CC 35 A=1,3
        GO TO (10,15,20),A
C
C
C          CCCCCCCCCCCCCCCCCCCCCCCCC
C          C                       C
C          C  MOMENT CALCULATIONS  C
C          C                       C
C          CCCCCCCCCCCCCCCCCCCCCCCCC
C
C
10      K=52
        L=3
        M=0
        GC TO 25
C
C
C           CCCCCCCCCCCCCCCCCCCCCCCC
C           C                      C
C           C  DRAG CALCULATIONS   C
C           C                      C
C           CCCCCCCCCCCCCCCCCCCCCCCC
C
C
15      K=15
        L=3
        M=52
        GC TC 25
```

```
C
C
C          CCCCCCCCCCCCCCCCCCCCCCC
C          C                     C
C          C  LIFT CALCULATIONS  C
C          C                     C
C          CCCCCCCCCCCCCCCCCCCCCCC
C
C
20    K=18
      L=2
      M=67
      GO TO 30
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                            C
C    C COMP1 PERFORMS A LEAST SQUARES OPERATION ON C
C    C THE TEST DATA FOR MOMENT AND DRAG; IT THEN  C
C    C PROVIDES THE SLOPES AND INTERCEPTS OF THE   C
C    C ASSUMED STRAIGHT LINE RELATION BETWEEN      C
C    C APPLIED LOAD AND LOAD CELL OUTPUT.          C
C    C                                            C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
25    CALL COMP1(K,L,M,A,COEFF,INCPT,POINTS)
      GO TO 35
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                            C
C    C COMP2 PERFORMS THE IDENTICAL OPERATIONS     C
C    C CARRIED OUT BY COMP1; HOWEVER,IT OPERATES   C
C    C ONLY ON LIFT DATA IN ORDER TO SIMPLIFY THE  C
C    C OVERALL OPERATIONS OF COMP1.                C
C    C                                            C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
30    CALL COMP2(K,L,M,COEFF,INCPT,POINTS)
35    CONTINUE
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                            C
C    C TRANS(I,J) IS THE BALANCE OUTPUT MATRIX; IT C
C    C CONVERTS LOAD CELL OUTPUT IN MILLIVOLTS TO  C
C    C MOMENT, DRAG AND LIFT.                      C
C    C                                            C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DET=COEFF(1,1)*COEFF(2,2)-COEFF(2,1)*COEFF(1,2)
      TRANS(1,1)=COEFF(2,2)/DET
      TRANS(2,2)=COEFF(1,1)/DET
      TRANS(1,2)=-COEFF(1,2)/DET
      TRANS(2,1)=-COEFF(2,1)/DET
      TRANS(3,1)=0.0
      TRANS(3,2)=0.0
      TRANS(3,3)=COEFF(3,3)
      DO 60 G=1,3
      GO TO (40,45,50),G
```

```
C
C
C         CCCCCCCCCCCCCCCCCCCCCCCC
C         C                      C
C         C  MOMENT CALCULATIONS  C
C         C                      C
C         CCCCCCCCCCCCCCCCCCCCCCCC
C
C
40     K=52
       L=3
       M=0
       WRITE(6,501)
       WRITE (6,502)
       WRITE (6,503)
       WRITE (6,504)
       GO TO 55
C
C
C          CCCCCCCCCCCCCCCCCCCCCCC
C          C                     C
C          C  DRAG CALCULATIONS  C
C          C                     C
C          CCCCCCCCCCCCCCCCCCCCCCC
C
C
45     K=15
       L=3
       M=52
       WRITE (6,505)
       WRITE (6,502)
       WRITE (6,506)
       WRITE (6,507)
       GO TO 55
C
C
C          CCCCCCCCCCCCCCCCCCCCCCCC
C          C                      C
C          C  LIFT CALCULATIONS   C
C          C                      C
C          CCCCCCCCCCCCCCCCCCCCCCCC
C
C
50     K=18
       L=2
       M=67
       WRITE (6,508)
       WRITE (6,509)
       WRITE (6,510)
       WRITE (6,511)
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                                C
C    C  COMP3 CALCULATES MEAN LOAD CELL OUTPUT         C
C    C  VALUES AND BALANCE LOADING VALUES BASED ON     C
C    C  THE SLOPES OBTAINED FROM COMP1 AND COMP2.      C
C    C  THE SUBPROGRAM ALSO COMPARES MEAN OUTPUTS       C
C    C  WITH ACTUAL OUTPUTS IN ORDER TO CALCULATE A    C
C    C  STANDARD DEVIATION FOR EACH CELL UNDER         C
C    C  INDEPENDENT LOADINGS.                          C
C    C                                                C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
```

```
55     CALL CCMP3(K,L,M,COEFF,INCPT,SIG,ACTVL,TRANS,
      XG,POINTS,DELTA,MEAN)
60     CONTINUE
       WRITE (6,512)
       DO 65 I=1,17
       WI(I)=1.
       F2(I)=INPUT(I+85,1)
       X(I)=INPUT(I+85,5)
65     CONTINUE
       M=17
       KM=-4
       CALL LSQPL2(M,KM,X,F2,WI,Y,DELY,B,SB,TITLE)
       WRITE (6,513)
       WRITE (6,514)
       WRITE (6,515)
       WRITE (6,516) (COEFF(1,J),J=1,3),(INCPT(1,J),
      XJ=1,3),(SIG(1,J),J=1,3)
       WRITE (6,517) (COEFF(2,J),J=1,3),(INCPT(2,J),
      XJ=1,3),(SIG(2,J),J=1,3)
       WRITE (6,518) (COEFF(3,J),J=1,3),(INCPT(3,J),
      XJ=1,3),(SIG(3,J),J=1,3)
C
C
C                 CCCCCCCCCCCCCC
C                 C            C
C                 C   FORMATS  C
C                 C            C
C                 CCCCCCCCCCCCCC
C
C
500    FORMAT (5F10.2)
501    FORMAT ('0',10(/),T32,'MOMENT DATA ANALYSIS',///)
502    FORMAT ('0',T32,'COMPARATIVE OUTPUTS',
      XT74,'COMPUTED LOADING')
503    FORMAT ('0',///,T4,'MOMENT',T24,'P1(MV)',T52,
      X'P2(MV)',T73,'MOMENT',T84,'DRAG')
504    FORMAT ('0',/,T3,'(IN-LBS)',T19,'DATA',T31,
      X'MEAN',T47,'DATA',T59,'MEAN',T73,'(IN-LBS)',
      XT85,'(LBS)',//)
505    FORMAT ('0',10(/),T33,'DRAG DATA ANALYSIS',///)
506    FORMAT ('0',///,T5,'DRAG',T23,'P1(MV)',T52,
      X'P2(MV)',T73,'MOMENT',T84,'DRAG')
507    FORMAT ('0',/,T4,'(LBS)',T19,'DATA',T31,'MEAN',
      XT47,'DATA',T59,'MEAN',T73,'(IN-LBS)',
      XT85,'(LBS)',//)
508    FORMAT ('0',10(/),T28,'LIFT DATA ANALYSIS',///)
509    FORMAT ('0',T30,'COMPARATIVE OUTPUTS',
      XT60,'COMPUTED LOAD')
510    FORMAT ('0',///,T6,'LIFT',T35,'P3(MV)',T66,'LIFT')
511    FORMAT ('0',/,T5,'(LBS)',T29,'DATA',T44,'MEAN',
      XT65,'(LBS)',//)
512    FORMAT ('C',10(/),T30,'ANGLE OF ATTACK DATA ANALYSIS'
513    FORMAT ('0',5(/),T36,'DATA FITTING VALUES',/)
514    FORMAT ('0',T16,'SLOPES',T45,'INTERCEPTS',T70,
      X'STANDARD DEVIATIONS',//)
515    FORMAT ('0',2(/),T9,'M',T19,'D',T29,'L',
      XT39,'M',T49,'D',T59,'L',T69,'M',T79,'D',T89,'L')
516    FORMAT ('0',/,T2,'P1',9F10.3)
517    FORMAT ('0',/,T2,'P2',9F10.3)
518    FORMAT ('0',T2,'P3',9F10.3)
       RETURN
       END
```

```
      SUBROUTINE COMP1(K,L,M,A,COEFF,INCPT,POINTS)
      INTEGER*4 A
      REAL*4 INPUT,INCPT
      DIMENSION POINTS(K,L),INPUT(102,5),COEFF(3,3),
     XINCPT(3,3)
      COMMON INPUT
C
C
C              CCCCCCCCCCCCCCC
C              C             C
C              C  INITIALIZE C
C              C             C
C              CCCCCCCCCCCCCCC
C
C
      SUMY=0.
      SUMP1=0.
      SUMP2=0.
      SMSQ1=0.
      SMSQ2=0.
      SMYP1=0.
      SMYP2=0.
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                C
C    C  FILL DATA SUBMATRIX POINTS(I,J) C
C    C                                C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      DO 110 I=1,K
      M=M+1
      POINTS(I,1)=INPUT(M,1)
      DO 105 J=2,L
      POINTS(I,J)=INPUT(M,J)
105   CONTINUE
C
C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C    C                                     C
C    C  CARRY OUT LEAST SQUARES OPERATIONS C
C    C                                     C
C    CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      SUMY=SUMY+POINTS(I,1)
      SUMP1=SUMP1+POINTS(I,2)
      SUMP2=SUMP2+POINTS(I,3)
      SQP1=POINTS(I,2)**2
      SQP2=POINTS(I,3)**2
      SMSQ1=SMSQ1+SQP1
      SMSQ2=SMSQ2+SQP2
      YP1=POINTS(I,1)*POINTS(I,2)
      YP2=POINTS(I,1)*POINTS(I,3)
      SMYP1=SMYP1+YP1
      SMYP2=SMYP2+YP2
110   CONTINUE
C
C
C      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      C                              C
C      C  STORE SLOPES AND INTERCEPTS C
C      C                              C
C      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C        IN COEFF(I,J) AND INCPT(I,J)
      DNM1=(K*SMSQ1-(SUMP1**2))
      DNM2=(K*SMSQ2-(SUMP2**2))
      SLOPE1=(K*SMYP1-SUMP1*SUMY)/DNM1
      SLOPE2=(K*SMYP2-SUMP2*SUMY)/DNM2
      CUT1=(SUMY*SMSQ1-SMYP1*SUMP1)/DNM1
```

```
      CUT2=(SUMY*SMSQ2-SMYP2*SUMP2)/DNM2
      COEFF(1,A)=1/SLOPE1
      COEFF(2,A)=1/SLOPE2
      COEFF(3,A)=0.0
      INCPT(1,A)=CUT1
      INCPT(2,A)=CUT2
      INCPT(3,A)=0.0
      RETURN
      END

      SUBROUTINE COMP2(K,L,M,COEFF,INCPT,POINTS)
      REAL*4 INPUT,INCPT
      DIMENSION POINTS(K,L),INPUT(102,5),COEFF(3,3),
     XINCPT(3,3)
      COMMON INPUT
C
C
C   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C   C                                            C
C   C   SAME OPERATIONAL STEPS AS SUBROUTINE COMP1  C
C   C                                            C
C   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      SUMY=0.
      SUMP3=0.
      SMSQ3=0.
      SMYP3=0.
      DO 205 I=1,K
      M=M+1
      POINTS(I,1)=INPUT(M,1)
      POINTS(I,2)=INPUT(M,4)
      SUMY=SUMY+POINTS(I,1)
      SUMP3=SUMP3+POINTS(I,2)
      SQP3=POINTS(I,2)**2
      SMSQ3=SMSQ3+SQP3
      YP3=POINTS(I,1)*POINTS(I,2)
      SMYP3=SMYP3+YP3
205   CONTINUE
      DNM3=(K*SMSQ3-(SUMP3**2))
      SLOPE3=(K*SMYP3-SUMP3*SUMY)/DNM3
      CUT3=(SUMY*SMSQ3-SMYP3*SUMP3)/DNM3
      COEFF(1,3)=0.0
      COEFF(2,3)=0.0
      COEFF(3,3)=SLOPE3
      INCPT(1,3)=0.0
      INCPT(2,3)=0.0
      INCPT(3,3)=CUT3
      RETURN
      END

      SUBROUTINE COMP3(K,L,M,COEFF,INCPT,SIG,ACTVL,
     XTRANS,G,POINTS,DELTA,MEAN)
      REAL*4 INCPT,MEAN,INPUT
      INTEGER*4 G
      DIMENSION ACTVL(K,3),POINTS(K,L),DELTA(K,2),
     XCOEFF(3,3),INCPT(3,3),SIG(3,3),MEAN(K,3),
     XTRANS(3,3),INPUT(102,5)
      COMMON INPUT
      DELSM1=0.
      DELSM2=0.
C
C
C   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C   C                                C
C   C   FILL DATA SUBMATRIX POINTS(I,J)  C
C   C                                C
C   CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
```

```
305   DO 330 I=1,K
      M=M+1
      POINTS(I,1)=INPUT(M,1)
      IF(G.EQ.3) GO TO 310
      POINTS(I,2)=INPUT(M,2)
      POINTS(I,3)=INPUT(M,3)
      GO TO 315
310   POINTS(I,2)=INPUT(M,4)
C
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     C                                    C
C     C  CALCULATE MEAN LOAD CELL OUTPUTS  C
C     C  AND BALANCE-COMPUTED LOADINGS     C
C     C                                    C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
315   MEAN(I,1)=POINTS(I,1)
      IF(G.EQ.3) GO TO 320
      MEAN(I,2)=POINTS(I,1)*COEFF(1,G)
      MEAN(I,3)=POINTS(I,1)*COEFF(2,G)
      ACTVL(I,1)=POINTS(I,2)*TRANS(1,1)+POINTS(I,3)*TRANS(1,2)
      ACTVL(I,2)=POINTS(I,2)*TRANS(2,1)+POINTS(I,3)*TRANS(2,2)
      WRITE (6,530) MEAN(I,1),POINTS(I,2),MEAN(I,2),POINTS(I,3),
     XMEAN(I,3),(ACTVL(I,J),J=1,2)
530   FORMAT (F8.1,3X,2F12.3,5X,2F12.3,5X,2F10.3)
      GO TO 325
320   MEAN(I,2)=POINTS(I,1)/COEFF(3,3)
      ACTVL(I,1)=POINTS(I,2)*COEFF(3,3)
      WRITE (6,531) MEAN(I,1),POINTS(I,2),MEAN(I,2),ACTVL(I,1)
531   FORMAT (F10.3,10X,2F15.4,10X,F10.3)
325   DELTA(I,1)=POINTS(I,2)-MEAN(I,2)
      DELSQ1=DELTA(I,1)**2
      DELSM1=DELSM1+DELSQ1
330   CONTINUE
      RG1=DELSM1/K
      SIG1=SQRT(RG1)
      GO TO (335,340,345),G
335   SIG(1,1)=SIG1
      GO TO 350
340   SIG(1,2)=SIG1
      GO TO 350
345   SIG(3,3)=SIG1
      GO TO 355
350   DO 355 I=1,K
      DELTA(I,2)=POINTS(I,3)-MEAN(I,3)
      DELSQ2=DELTA(I,2)**2
      DELSM2=DELSM2+DELSQ2
355   CONTINUE
      RG2=DELSM2/K
      SIG2=SQRT(RG2)
      IF(G.EQ.1) SIG(2,1)=SIG2
      IF(G.EQ.2) SIG(2,2)=SIG2
      SIG(3,1)=0.0
      SIG(3,2)=0.0
      SIG(1,3)=0.0
      SIG(2,3)=0.0
      RETURN
      END
```

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A three-component balance system for use in measuring drag and lift forces as well as pitching moments acting on a wind tunnel model is presently available in the Department of Aeronautics. The original manual counterweight readout procedure was considered obsolete from the standpoint of data acquisition; therefore, a revision was incorporated using strain gauge load cells. The design and installation of the electrical readout system was

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accomplished. Calibration procedures were devised and performed in order to develop a loading output matrix for use with a rapid data acquisition system and compatibility with an analog-digital computer program.

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